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PRODUCTION FABRICATION
TREATMENT APPLICATION

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ARTICLES

CURRENT METALLURGICAL ABSTRACTS

WATCH COSTS COME DOWN

- - - *when the steel is right!*

TAKE these two gears, for instance. One was the despair of the machine shop. "The toughest gear to cut I ever saw," said the superintendent. Tool life was so short that 25% of the machining time was spent changing tools. And the gears were noisy, wore badly.

The other is the same gear, but made of different steel-S. A. E. 4615. With this new steel, machining is simple. There's no peeling of the tool. Gear teeth finish is smooth and uniform. Gears operate quietly — last longer. And production is up. Costs are down.

. . .

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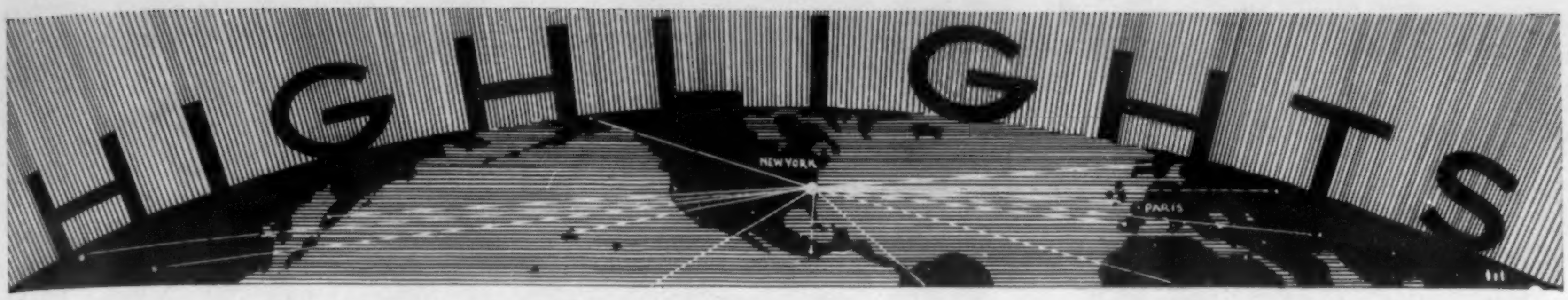
US STEEL

UNITED STATES STEEL



Written by the Abstract Section Editors and the Editorial Staff

DO YOU want to know what metallurgical engineers are saying, the world over? Look in the Current Metallurgical Abstracts. Here are some of the points covered by authors whose articles are abstracted in this issue.

Bugs Now Out of Hadsel Mill

The Hadsel mill was withdrawn from the market when it failed in some instances to live up to promising first reports. According to Hardinge (page MA 51 L 4) the bugs are now out of it.—J.A.

Very Thick Pulps Advantageous

In a paper curiously entitled, "Some Effects of Diluting a Flotation Pulp," Ralston and King (page MA 51 L 5) find very thick pulps (45 per cent solids), advantageous. This forecasts trouble (and business) for companies making thickeners.—J.A.

Steel Refining by the Perrin Process

A new French process of steel refining, the Perrin, is much talked-about, but little on it has yet been published. The account in English, by Pugh, (page MA 54 L 2) gives a good idea of the process.—H.W.G.

Hydrogen Absorption and Unsound Stainless Steel

Speranski (page MA 54 L 3) stresses the harmfulness of moisture in the charge and resulting hydrogen absorption in a melt of stainless steel, which produces unsoundness.—H.W.G.

A Confusion in Terminology

Michel's terminology, (page MA 57 L 9) referring to a "martensitic" Cr steel of 170-200 Brinell, seems a bit odd. We judge that he is really talking about making the steel ferritic rather than martensitic before machining.—H.W.G.

Backhand Oxyacetylene Welding

In the early days of oxyacetylene welding, great stress was laid on finishing the welds with a smooth surface, to have the work appear as if seamless drawn. The natural consequence was the development of the "leftward" or forehand method of wash welding. Unfortunately, the present-day economical application of this process is limited to thicknesses of not over approximately ⅛" for steel. Furthermore, forehand welding is not conducive to the production of ductile, high-strength welds on heavier work.

Gradually, engineers overcame their aversion to visible ripple welds and learned to appreciate high-quality workmanship. When "rightward" or backhand oxyacetylene welding was generally introduced a few years ago it revolutionized the art. With this method, oxyacetylene welding now can be applied efficiently and economically to steel plates or sections of practically any thickness. Welding speed is increased at least 30-50% and gas consumptions are reduced proportionately. A comparatively narrow vee (60-70°) is used, requiring less filler metal. The welding flame is not moved from side-to-side across the vee, but its cone is brought in close proximity to the work and the full intensity of the heat utilized. By directing the flame against the finished weld, the molten bath can be kept much smaller and consequently easier to control, the molten metal, welding rod and section of completed weld at high temperature are protected from oxidation by the envelope of the flame, and the area of the base metal heated is smaller, thus reducing the distortion.

Multi-flame tips, used in conjunction with backhand oxyacetylene welding have recently effected further marked increases in welding speed and corresponding reductions in unit costs (page MA 65 L 8 and MA 65 L 8).—E.V.D.

Welding and Monocoque Aeroplane Construction

Monocoque designs for aeroplanes, employing a stressed skin of aluminum alloy, are tending to replace welded steel construction in recent years. The applications for oxyacetylene and metallic arc welding in aircraft production appear to have reached a peak in 1931 and 1932 when better than 75 per cent of all fuselages manufactured in the United States were made of welded steel. Except for engine mounts, landing gears and miscellaneous fittings, it now seems likely that resistance spot-welding may offer greater advantages for the new type of structure and continue to find wider use in this field (page MA 65 L 9).—E.V.D.

Tin Rayon?

Not long ago, direct rolling became a topic for much discussion. Perhaps tin rayon will be the next, because Tammann and Moritz (page MA 74 R 2) have been able to make wire of some of the low-melting metals and alloys by squirting them, in the molten condition, from small conical nozzles.—J.S.M.

A Tip for Teachers

The teacher may be interested in Primrose's method of obtaining pearlite, troostite, sorbite and martensite in a single specimen of carbon steel. This consists of quenching a previously pearlitic steel while undergoing transformation upon heating (page MA 74 R 3). —J.S.M.

Beryllium: Ave, Salve, but not Vale!

Inasmuch as beryllium was hailed here and there a few years ago as the fair-haired boy of alloying elements, it is of interest to note that Misch (page MA 74 R 5) reports structures and constants of compounds of this element and copper, nickel and iron. The user of precipitation-hardened alloys probably does not care what compound jumps out; and the research man, however, is likely to find the information useful. —J.S.M.

Training of Welders

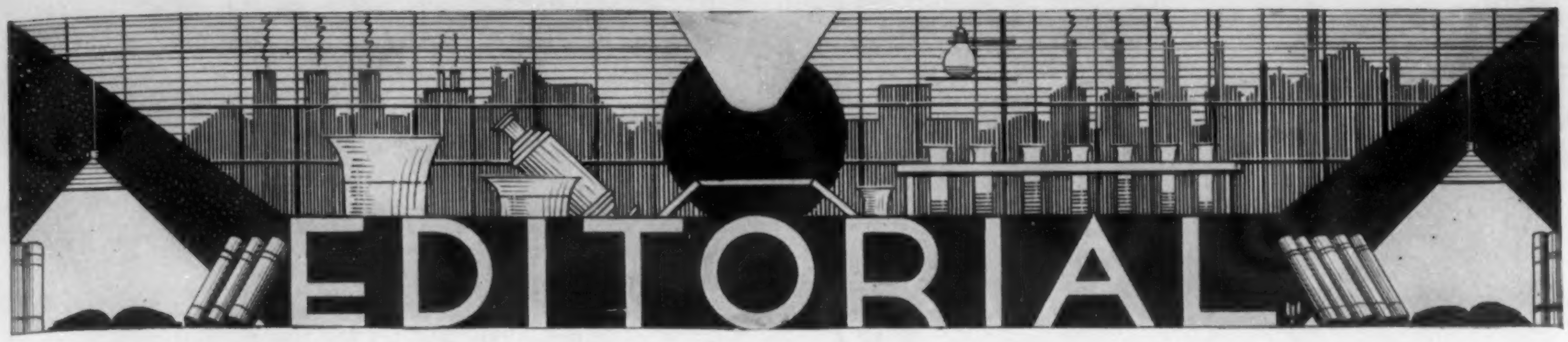
The growth of welding has been so rapid that the demand for good welders nearly always has exceeded the supply. The best methods for training welders to take their places in almost every branch of manufacture have by no means been settled.

Regulatory bodies on every hand have recognized welding as an accepted method of construction. This places a great responsibility upon manufacturers to allow nothing to happen that might destroy the confidence that has been won. It is vital that all strength welds be so well made that there may be no weakness in any part which might result in a failure and possible loss of human life. Hence, the welding industry should give every encouragement to schools that supply a large number of good welders to the trade and adequately train these men to assure a high standard of craftsmanship.

Welding instructions, on the one hand, may be concerned almost entirely with fundamental scientific principles of the art or, on the other hand, solely with training in skill and manipulation to produce good work. Between these two extremes there exists a variety of needs requiring varying proportions of each type of instruction. Opinions differ regarding the relative amounts of theory and practice which should be included in a given course in welding and, where more than one process is to be taught, the percentage of the total time to be devoted to each process (page MA 65 L 10).—E.V.D.

Some Why's of Chromium Steels

Study of the constitution of chromium steels is complicated by the existence of chromium carbides. Phase diagrams neglecting this fact have been published—the reason being to avoid excessive complexity—but these are not suited to rational and complete interpretation of observed behavior. A partial diagram, however, which is capable of such interpretation has been constructed by Tofaute, Sponheuer and Bennek (page MA 74 R 7) for alloys containing lp to 12 per cent chromium. Vertical sections show at once why the "simplified" diagrams do not account for the available data.—J.S.M.



Fifty Years of Aluminum

THE reference to Blough's early research work on aluminum in the article by Dix, in this issue, interested us, for it was the fact that Blough was making good that led indirectly to our own entrance, a little over 25 years ago, into metallurgical research. The Aluminum Castings Co. noted that research was of benefit to the Aluminum company, and decided to follow suit. That Blough was a Cornell product led to the Castings company inquiring there for a candidate, and our own connection with the Castings company resulted.

In those early days, the information developed by Blough and his men was pretty closely held and publication of technical information was rare. As time went on, a more enlightened policy was adopted, one ventures to think very largely through the influence of far-sighted technical men, such as Blough himself, Dr. Jeffries, Mr. Colby, and of the group such as Dr. Frary, Messrs. Edwards, Dix, Templin, etc., which they later called to their aid.

These men realized that a material such as aluminum, with quite different properties from the older commercial metals, with advantages and drawbacks of its own, is used because of its peculiar fitness for a given engineering purpose and that the real choice between materials is made by the engineering staff of the user, which in turn depends on the metallurgical staff for verification of the maker's claims. Thus the real audience that must be reached in order to put aluminum into new commercial uses, is the metallurgical engineer. Very wisely, the Aluminum company has developed the policy of finding out the facts by exhaustive research and presenting them in such fashion that they carry conviction to the scientist and technician that they are facts and not unsubstantiated claims.

One does not need to repeat the work reported by the Aluminum company's research staff in order to accept it as the most nearly accurate information available at that date. The degree of credence given to the data reported from the Aluminum company's research and engineering laboratories has few parallels. This seems to us to be a real achievement, and, in the long run, perhaps the greatest one of the whole fifty years.—H. W. G.

Thoughts on Dr. Hoyt's Appraisal of Notched Bar Testing

FAILURES in metal parts may occur (1) by exceeding the elastic limit and thus getting stretching of crumpling, like a fender; (2) by exceeding the endurance limit, like a spring leaf; (3) by impact, like dropping a glass on a cement floor, or knocking a chip out of the axe instead of the log, by chopping into a knot on a frosty morning with a poor axe.

Long ago Atchison stated that the three criteria an engineer should apply to his steel are the proof load, the fatigue range, and the notched-bar value. Tensile strength is not in this list, and in fact it is probably more interesting than it is important in avoidance of actual failures. Perhaps it is so much cited in evaluation of materials because it is numerically the largest of the commonly determined values and sounds the most imposing. It does come in, in a fashion, because in ferrous materials it usually, though not always, happens that the fatigue range is roughly equal to the tensile strength. But in so far as this rough comparison serves, the far cheaper Brinell test would do as well as the tensile. Of course, in non-ferrous alloys the endurance limit always has to be directly determined, as it must be for any fine-haired, appraisal of ferrous alloys.

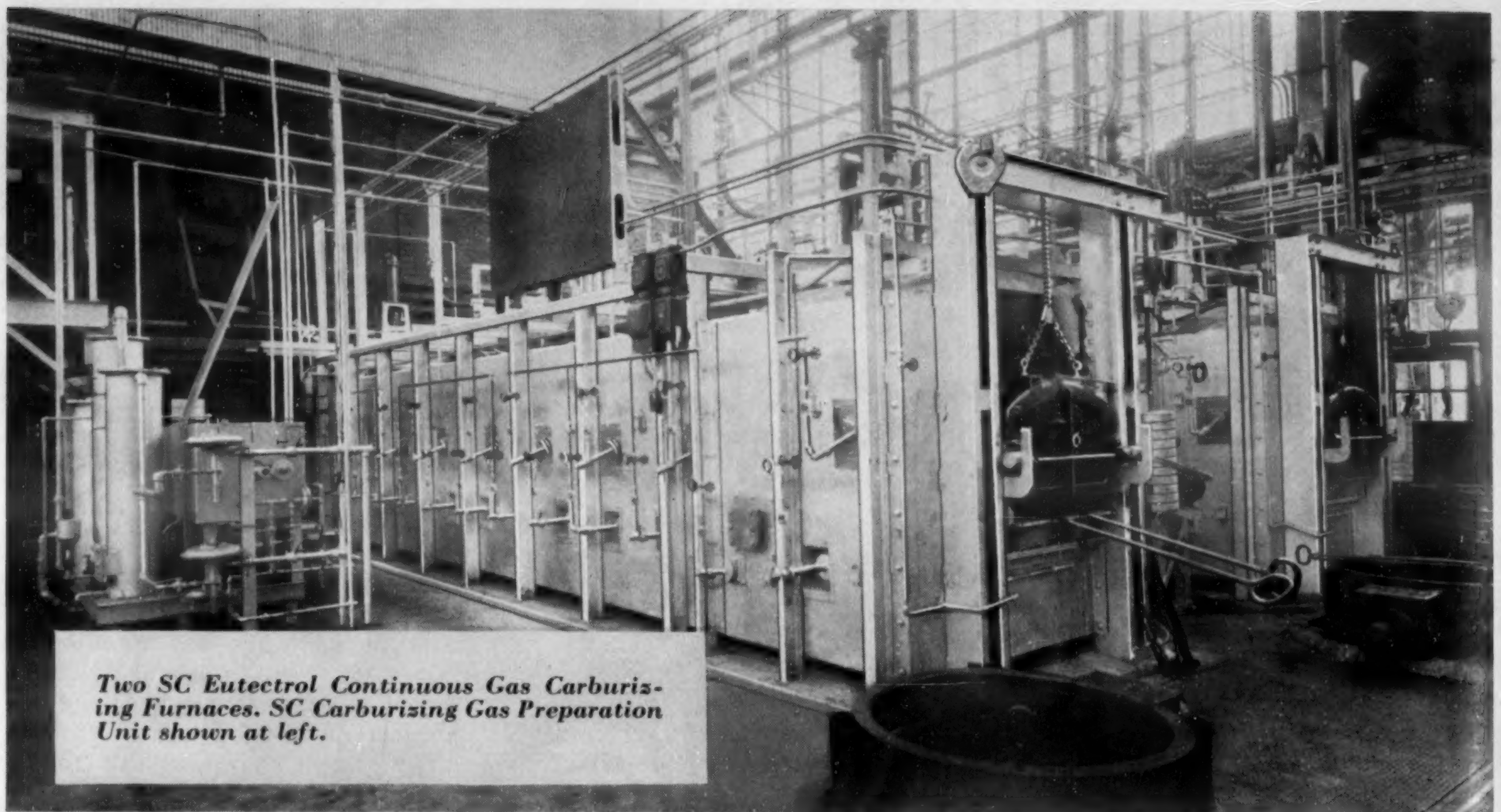
It may be straining matters a bit to demand a "proof load" in order to establish that the true elastic limit desired has not been exceeded, when the ordinary tensile test and its stress strain diagram, tell more and are not much more costly. At any rate, from the early days of materials testing, static failures have been pretty well guarded against by tensile testing and the way to make the test is well understood.

Fatigue failures puzzled engineers who had designed on the yield strength basis until Prof. Moore, and many other workers in that field, brought about a better understanding of the effect of repeated stress, of endurance testing methods, and of local stress concentration. However, the polished-specimen endurance-limit basis of engineering design still leaves some corners unswept so that "crackless plasticity" and the "damage line," i.e.—ability to withstand overstress, are being studied in order to explain and prevent the residuum of failures that occur in spite of intelligent design and intelligent testing on the basis of present knowledge.

The third cause of failure, that occurring under impact, especially when the impact is applied to a part so designed or mis-designed as to have stress concentration, as at a notch, is now being given thoughtful attention. Among those who are outstanding in the study of notch-brittleness is Dr. Hoyt, long an advocate of notched bar testing, who discusses the problem in illuminating fashion in the article now being published serially in METALS & ALLOYS. We can recall when his was "a voice crying in the wilderness" and when impact tests were not at all in good odor among most engineers. Metallurgists generally turned up their noses, too.

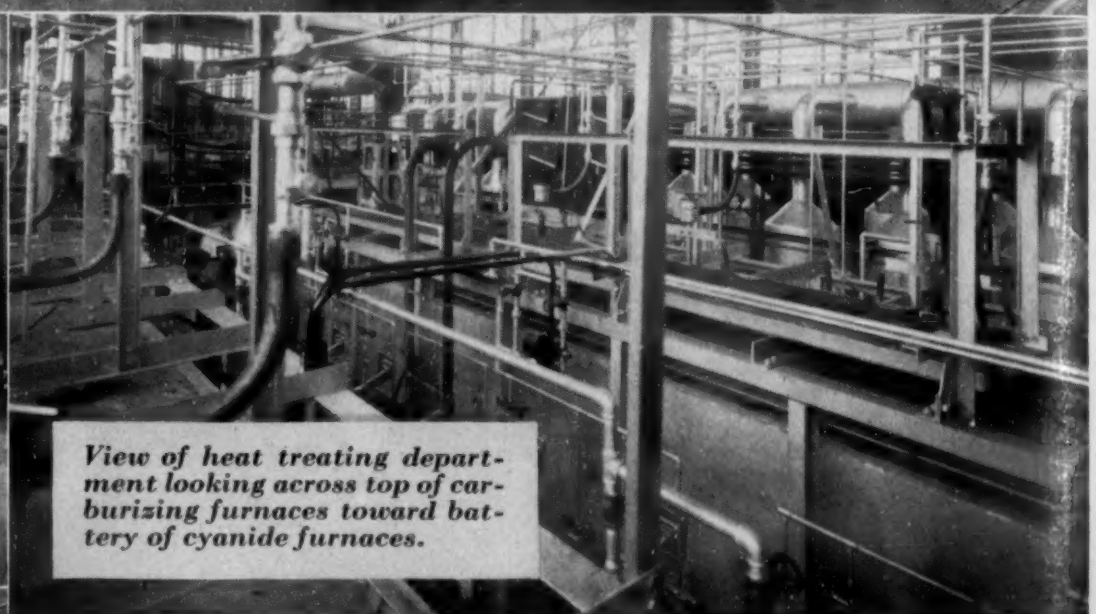
The engineers and metallurgists of the arsenals of the world, however, were very sure that there was a good correlation between poor notched bar tests and big guns that would burst. Aircraft designers and metallurgists found that the proper steels for airplane

(Continued on page 34)



Two SC Eutectrol Continuous Gas Carburizing Furnaces. SC Carburizing Gas Preparation Unit shown at left.

Fifteen SC Cyanide Furnaces.



View of heat treating department looking across top of carburizing furnaces toward battery of cyanide furnaces.

Five-Station Lead Hardening Furnace.

INDUSTRY'S DEPENDENCE

In the Heat Treating Department of a large-scale production industry there must be utmost dependability. Inspection of heat treated parts is exacting, tolerances are held to close limits, rejects are ruinous. Continuous and economical operation with a minimum of maintenance is vital.

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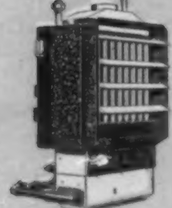

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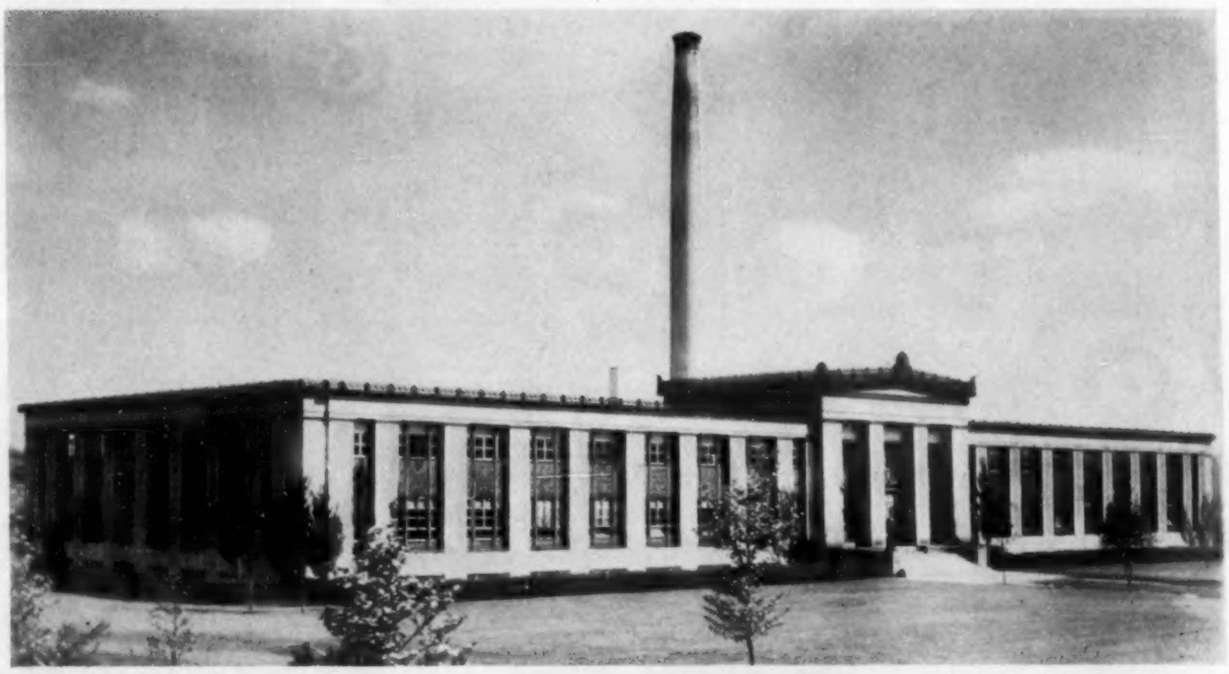
Fifty Years of Aluminum Alloy Development

By E. H. DIX, JR. and J. J. BOWMAN

Chief Metallurgist and Metallurgical Division, respectively, Aluminum Research Laboratories, New Kensington, Pa.



The Aluminum Research Laboratories. The modern counterpart of Charles M. Hall's woodshed laboratory.

FIFTY YEARS AGO this month, Feb. 23, 1886, to be exact, Charles M. Hall first succeeded in producing aluminum by the electrolytic reduction process. The metal itself was not a new discovery, as Oersted had isolated it in his laboratory some 61 years earlier, and it was even then (1886) in commercial production.

Hall at the age of 22 achieved what many great chemists had failed to do after a half century of work. Interested in chemistry from boyhood, he spent the year after his graduation from Oberlin College in a search for a cheap and convenient method of separating aluminum from its ores. Early in February, 1886, he found that cryolite was the bath needed for his electrolytic process and on the 23rd of that month, when he substituted a carbon for a clay crucible, he produced the first shiny globules of metallic aluminum. With this discovery by Hall was born the modern commercial history of the aluminum industry.

Early Samples of Aluminum

Prior to 1886 aluminum was commercially produced by the sodium reaction process but it was a rather costly metal and was, therefore, principally employed in jewelry and novelties. Perhaps the largest piece of jewelry was the 100-ounce cap piece for the top of the Washington Monument produced at a cost of $225. When first made, it was displayed in the window of Tiffany's, New York. The cap was of "pure" aluminum with the impurities, iron, silicon and copper, in about the same amounts as are found today in commercially pure metal. Newspaper accounts of the installation of the cap in 1884 stated that aluminum was used abroad for buttons and other parts of the soldiers' uniforms in order to reduce weight and permit them to carry more ammunition. This was the first recognition of the importance of the light weight of aluminum in transportation.

Any attempt to give in detail the history of aluminum alloy development during the 50 years from the Hall discovery to the present would be impossible in the space limitations of the present article and would make dry and uninteresting reading. Instead, the authors will try to touch upon the alloys which have played an important part in the growth of the industry in the United States and will mention only those developments abroad which have been influential in affecting the course of development here. No attempt

will be made to assign individual credit for the development of a number of important alloys, for in these developments many research and production men have had their influence. Occasionally those names, recognized as being associated with major developments, will be mentioned.

Prior to the Hall invention, laboratory studies of the properties of many aluminum alloys had been made but, owing to the high cost of the metal at that time, the combinations of principal interest were those of pleasing color or with special properties suitable for instruments and similar applications. Except for the use of the metal in aluminum bronze structural applications as we know them today did not exist.

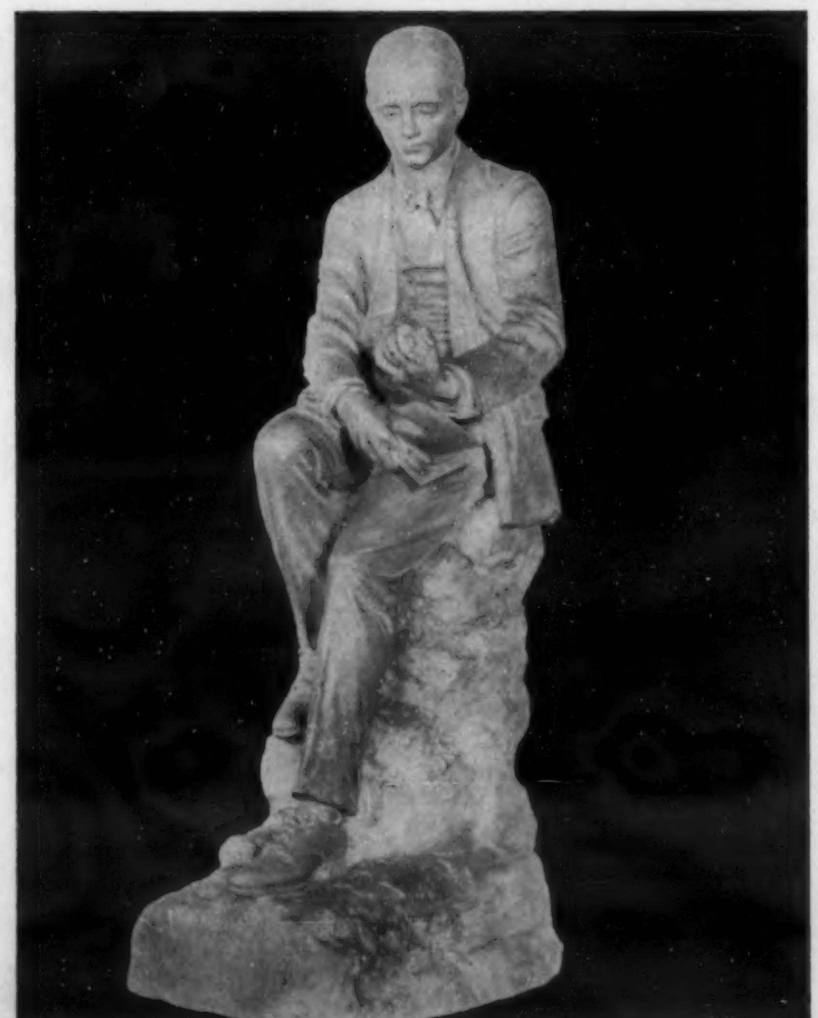
With the successful production of aluminum by the Hall process the necessity of alloying some other metal or metals with it to improve the mechanical properties or casting characteristics became evident. The alloys used in the first 10 or 15 years after this are rather hard to accurately determine, however, as great secrecy surrounded those which proved most popular. A review of the literature indicates, though, that common additions included zinc, nickel, copper, iron, tin and manganese.

Zinc an Early Addition

It was recognized at an early date that zinc additions produced marked increases in strength, and aluminum-zinc alloys were used frequently. One of these was a 33 per cent zinc casting alloy developed by Andrews and Hunt at Cornell University and subsequently popularized as "Sibley Alloy." The wrought alloys generally did not contain such high zinc, and indeed 15 per cent soon became the maximum for both cast and wrought compositions.

This early choice of zinc was unfortunate and added greatly to the problems which beset the early utilization of aluminum. The alloys were hot-short, had poor corrosion resistance and, with high zinc content, were unstable. Efforts to improve the situation led to the use of copper as an alloying element both separately and in combination with zinc. An old alloy of the aluminum-copper-zinc type was one commonly referred to as No. 31 alloy.

Charles Martin Hall. A statue cast from the metal he made commercially useful.



Transition to Al-Cu Alloys

The transition to aluminum-copper alloys apparently was just well under way when the automobile industry was born. This new industry soon became a substantial customer for aluminum castings and was partial to the copper alloys because they were somewhat lighter than those containing zinc. The combined circumstances eventually resulted in the establishment of the well-known No. 12 alloy containing 8 per cent copper. For the next several years, this composition was the principal casting alloy used—in fact, it remained the mainstay of the foundry business until fairly recently.

About the earliest wrought alloy of record in this country was one containing apparently about 4 per cent nickel. This alloy was advertised for sale in sheet form as early as 1894. Manufacturing difficulties almost immediately led to the substitution of a 2 per cent copper alloy. This alloy also was used for the first electrical transmission lines, but high electrical conductivity combined with the required mechanical properties seemed impossible. The ingenuity of an electrical engineer of the Aluminum Co. of America, William Hoopes, did what the metallurgist was unable to accomplish. Mr. Hoopes designed a cable combining strands of pure aluminum, for conductivity, with a steel core, for strength. The development occurred in two steps, first the stranded aluminum-cable and second, the steel reinforcing core. This now-well-known A.C.S.R. (aluminum cable steel reinforced) is today satisfactorily serving the power companies in some 430,000 miles of lines.

Birth of the 3S Alloy

It was under similar circumstances that, in 1906, the development of the oldest present-day wrought alloy was achieved. Sheet aluminum camera cases, to which an imitation leather covering was cemented with a corrosive adhesive, were being returned in a badly corroded condition from areas having a hot, humid climate and, unless something was soon done, a good customer would be lost. Dr. Earl Blough, now acknowledged as a pioneer in the aluminum industry of this country, but then a recent graduate from Cornell University working on a project for treating aluminum to make it look like copper or brass, took time from this, to his mind, unimportant project to study the new problem. Using the Frick Conservatory (in Pittsburgh) as a testing ground, because its atmosphere simulated that causing trouble, Dr. Blough expeditiously arrived at substantially the present 3S composition (1.25% Mn).

In accord with the existing custom, the alloy was not patented nor was its composition spread over the pages of the technical journals. In fact, when first produced the alloy was assigned the number previously used for the inferior composition it supplanted. The development not only saved the business immediately threatened, but also served to introduce a material of moderate strength and of an entirely new order of corrosion resistance. Curiously enough, the alloy is but now receiving recognition in technical circles of

certain foreign countries, although it has been used in substantial amounts in this country for nearly 30 years.

To the further credit of 3S, it should be pointed out that nearly a quarter of a century passed before a new common alloy (strain-hardened type) was sought for and developed. This later development was 4S, an alloy similar in composition to 3S except for the addition of about 1 per cent magnesium but with substantially higher strength. For applications requiring strengths higher than available with 3S but lower than commonly developed by the heat-treated alloys, 4S serves an excellent purpose.

Duralumin Appeared in 1910

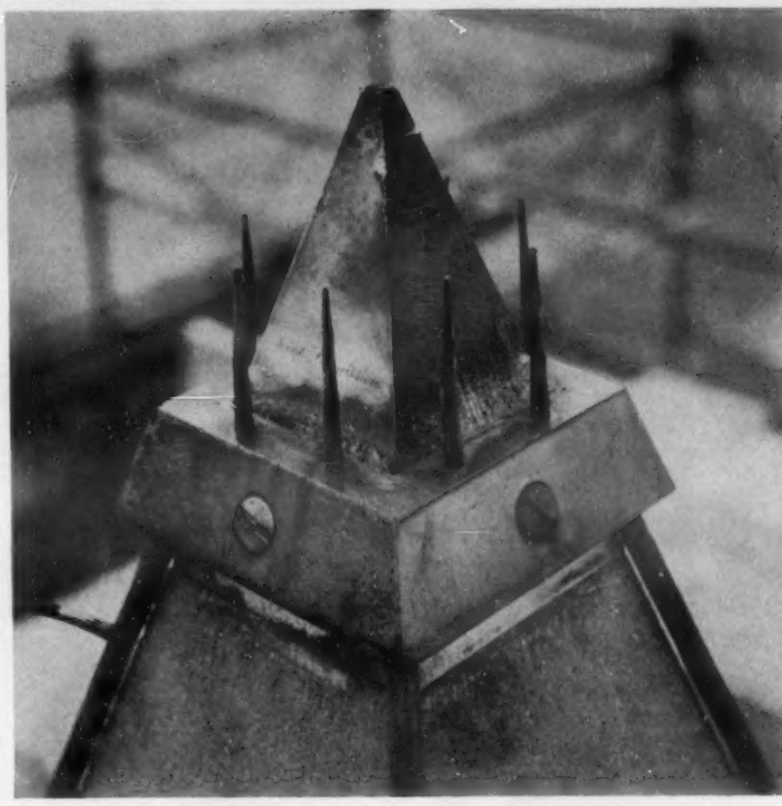
About 1910 a development, which was destined to have far reaching effect not only on aluminum alloy development but on all metallurgical thought, was announced. This was the discovery by Wilm of the heat-treatable alloy duralumin; the result of a systematic study of the aluminum-copper-manganese-magnesium alloys. About 1906, he found that some of these compositions could be heat treated and would subsequently age-harden. Further study was necessary to define the treatment necessary for consistent results so that, although the composition patent was issued in 1907, the heat treatment patent was not issued until 1909.

The Wilm discovery was much more than an alloy invention because the composition which he developed was susceptible to a marked improvement in properties by heat treatment. Although Wilm's invention resulted from systematic work, there is little in the literature to indicate that he understood the reasons for the effectiveness of his invention. It remained for Merica, Waltenberg and Scott, about nine years later, to announce their precipitation-hardening theory, which satisfactorily explained the mechanism of hardening in duralumin and now is a principle upon which not only heat treatable aluminum alloys but also similar alloys of other bases are being developed.

The Wilm alloy, familiarly called duralumin, was very remarkable in that it employed the two best solid solution hardening constituents, $CuAl_2$ and Mg_2Si, and the best insoluble element for grain size control and reinforcement of the solid solution matrix, in amounts so well selected that the composition has persisted to the present time with relatively little change. Even though the composition has not changed, methods of alloying and of fabricating have advanced tremendously, so that the duralumin (17S-T) produced in America today is a vastly superior material, having recognized exceptional uniformity of properties, much improved corrosion resistance, and availability in forms and sizes hardly anticipated in Wilm's time, be it large sheets for truck bodies or extruded and rolled structural shapes for railroad cars and bridges.

Modification of Duralumin

Although the Wilm composition has persisted without change, many useful modifications have been developed to meet specific requirements or particular fields of application. The advanced development of the forging art in America is due in no small measure to the development, by Jeffries and Archer and their associates, of the Aluminum Research Laboratories, of two alloys employing separately the solid solution hardening elements of the Wilm alloy. The alloy 25S depends on $CuAl_2$ and the alloy 51S on Mg_2Si, but both alloys have added silicon which aids materially in attaining high strengths in the precipitation hardened temper. The addition of silicon to the duralumin composition also was found to make this alloy amenable to improvement in strength by artificial aging, from which resulted the alloy compositions C17S, super-duralumin and 14S. There were also the further modifications obtained by reducing the amount of alloying elements to obtain improved workability in such alloys as A and B17S.



The Crown Jewel of the Washington Monument. During fifty years' exposure to the elements, lightning alone was able to leave an impression.

At this point should be mentioned a group of alloys developed by Victor Hybinette, in which Mg_2Si is the principal hardening element. They also contain about 1 per cent of nickel, some copper and zinc, and very small amounts of other elements such as chromium, molybdenum and manganese. These wrought alloys have the reputation for good workability but cover quite a range in workability and physical properties. They were originally known as Hyblum but have more recently been called Nicralumin.

Alclad for Aircraft

Within the last decade the contributions of the Aluminum Research Laboratories have dominated the aluminum alloy development in the United States. In the wrought alloy field, Alclad sheet was the first major development of an aircraft structural material since Wilm's discovery. When duralumin sheet was first used in aircraft, the necessity for protecting the thin sections from corrosion was not appreciated, and the consequent corrosion of these thin sections was a major factor in retarding the further development of aluminum alloy aircraft structures. Methods of protection by adequate paint coatings, using an oxide film produced electrolytically (anodic oxidation) as a base, were meeting with a fair degree of success when the first Alclad sheet was produced commercially and employed for the metal covering of the only metalclad airship, the Navy ZMC-2. This metal gas container, formed of Alclad 17S-T sheet only 0.0095 in. thick, has now successfully withstood six years of service without any surface protection and with no harmful corrosion. Aluminum coatings on aluminum alloys had been the subject of at least two foreign patents and the Bureau of Standards had demonstrated the

The Only Metal-Clad Dirigible. Helium Gas is held in this riveted shell of 0.0095 in.-thick Alclad 17S-T sheet, which has satisfactorily withstood atmospheric corrosion without any surface protection for more than six years.

efficacy of a sprayed aluminum coating on 17S as protection against corrosion; but it remained for the Aluminum Co. of America to successfully produce aluminum-coated sheet commercially and to recognize that the higher solution potential of the pure aluminum exercised electrolytic protection over the core, in which the solution potential had been lowered by copper in solid solution.

This principle of electrolytic protection has been further utilized in developing other Alclad combinations, in which a core alloy of such solution potential that it would not be protected by pure aluminum is coated with an alloy to which elements have been added to raise the solution potential and so give the necessary electrolytic protection. Such a material, Alclad 72S(3S), has been successfully used for aluminum Mason jar caps and containers in which a high resistance to pitting is required.

Although the coating on Alclad 17S-T sheet weighs scarcely as much as a good protective paint coating, there has been considerable reluctance on the part of aircraft engineers to employ this somewhat higher-cost material because it requires a sacrifice in initial strength of the structure. To meet this objection, an alloy core of the duralumin type was developed so that in Alclad form, the product would have the strength of unclad duralumin. Again the aircraft engineers, concerned primarily with weight reduction, seemed to prefer the additional strength obtained in the new core alloy without the protective, pure-aluminum coating with its resultant added weight. Thus was born another modification of the duralumin composition (24S) of higher strength and equivalent corrosion resistance.

As the exceptional merit of the Alclad products became more obvious, there has been a gradual but steady increase in the use of Alclad 17S and Alclad 24S sheet, in both the T and RT tempers, until today one of the principal manufacturers of transport planes is almost exclusively using Alclad 24S without any surface protection.

27S and 53S Developed

Modern alloy development is based upon well-grounded metallurgical fundamentals, but even so an important strong alloy development resulted from almost pure chance. J. A. Nock, Jr., of the Aluminum Research Laboratories, was surprised one day to find that a duralumin-type alloy, which he had made and heat treated, had a yield strength fully 50 per cent higher than normal. The reason for this improvement remained a mystery for several years despite repeated efforts to find the cause. Finally persistence won and a new structural aluminum alloy, 27S, having an especially high yield strength and, still more remarkable, good corrosion resistance in the artificially aged temper was developed.

Since the time of Charles Martin Hall, the reduction plants in the United States, spurred on by the development of a new process (Hoopes cell) for electrolytically producing aluminum of exceptionally high purity, gradually have increased the average purity of the aluminum produced. This has permitted the development of alloys of exceptional corrosion resistance by the employment of high purity aluminum ingot. As a product of depression research in the Aluminum Co. of America, 53S was developed to meet a specific requirement of extruded window sections. High corrosion resistance was necessary and a high purity aluminum base indicated. Actually, the new alloy was on the market 60 days after its requirements had been defined.

Fundamental alloy constitutional studies, conducted patiently in the laboratory over a period of years, formed the basis for its development. Well developed accelerated laboratory testing methods and close cooperation of research and production departments combined to make this rapid development possible. The alloy composition is simple enough but its success depends on intelligent selection and careful control not only of the intentional alloying elements but also of the usual impurities.

So successful was this alloy, intended primarily for

extruded window sections, that it is now finding large application in a variety of extruded sections for architectural applications, in sheet for railroad and bus construction and in various forms for marine use.

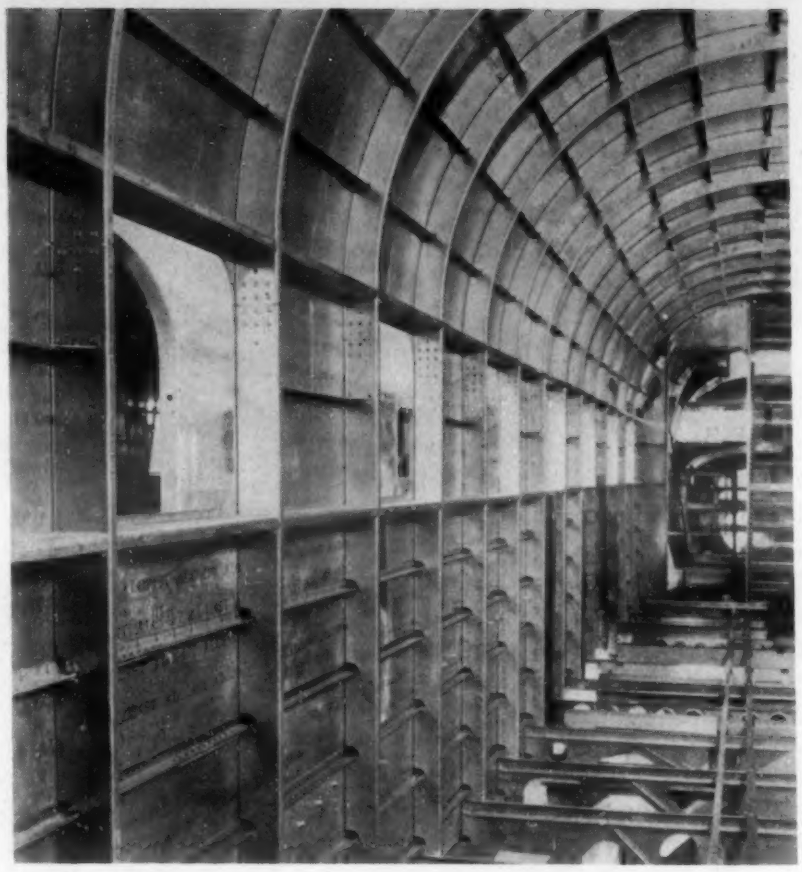
Paralleling the development of 53S in the utilization of high purity metal to obtain maximum corrosion resistance, and also during the depression period, came the alloy 52S, containing 2.5 per cent magnesium and 0.25 per cent chromium. The magnesium concentration was selected so as to give a non-heat treatable alloy of moderate strength which could be produced at a commercially reasonable price. Both in this and in the use of high purity aluminum, this alloy differs from many foreign compositions employing substantially greater amounts of magnesium.

During the war period the use of aluminum castings greatly increased and several modifications of No. 12 alloy were used. One of these was the addition of iron to improve the foundry characteristics while another was the addition of magnesium to increase the strength. These modified alloys were never very popular. Later, additions of zinc, partly as a result of mixed scrap, were made to No. 12 alloy, and in one important modification the silicon content was increased to give an alloy of better casting qualities, so that today the original No. 12 alloy composition is of minor importance.

When the exigencies of the war had passed and time was available for systematic examination of possible casting alloys, the aluminum-copper-iron-zinc series was studied. After some investigation, an alloy designated as No. 145 was introduced and found to consistently produce sand castings with a good combination of strength and ductility.

The Y Alloy

About this time (1914-19) English metallurgists likewise had been working with a number of casting alloys but had been more interested in aluminum-zinc or aluminum-copper-zinc compositions. However, they had examined a number of other alloys, because of the poor high-temperature strength of alloys containing zinc, and had selected the now-famous Y alloy

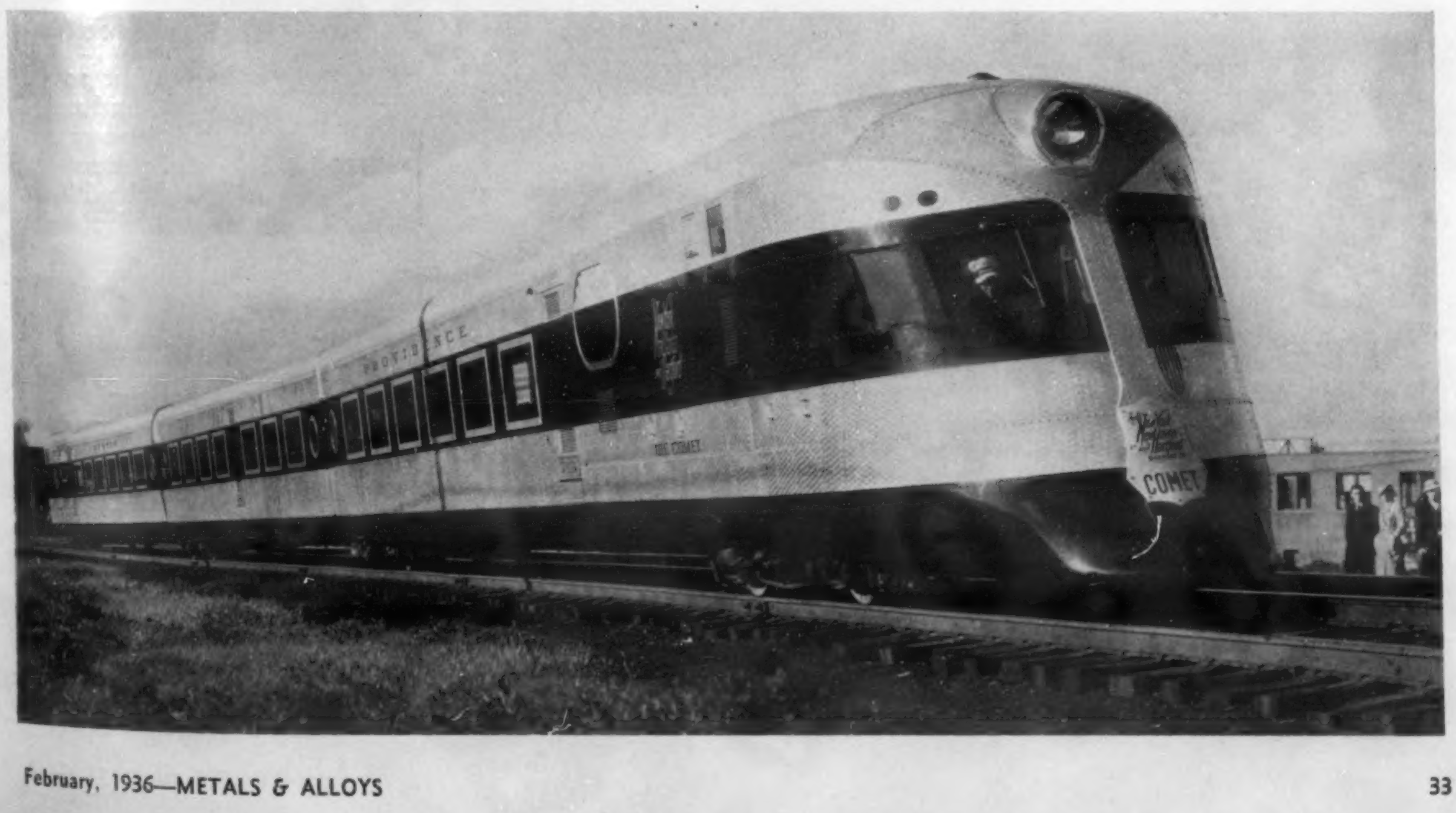


The Alclad 24S-T Interior Structure of a Douglas Transport. No surface protection is required for this use.

(nominally 4% copper, 2% nickel, 1.5% magnesium, balance aluminum) for high-temperature applications. This alloy, with modifications, has been used in this country for castings and forgings (18S) and, in England, it has formed the basis for the RR series of cast and forged materials.

After the war the demand in this country for higher-strength castings became more insistent and thorough studies of heat treatable alloys were undertaken. Some experiments in the heat treatment of castings had been carried out with indifferent success but Jeffries and Archer finally determined the conditions necessary for success and a heat-treated 4 per cent copper alloy (195) was introduced. A modification of this alloy

The Modern Style in Railroad Equipment. The aluminum "Comet," which utilized the results of modern aluminum alloy research.



(196—containing a small amount of magnesium) was also developed, but the original alloy continues to be used for a large part of the aluminum castings made.

About 1920, casting alloy developments were accelerated by Pacz' discovery of modified silicon alloys. Previously, it was the general belief that silicon additions were undesirable but study demonstrated that certain of the low-silicon alloys were of value. They have since served both a useful purpose in the foundry and as the basis for further developments.

Pacz Alloys and Die Castings

Although Pacz' modified, high-silicon alloys never proved very popular for sand castings in this country, the establishment of the aluminum die casting industry in the United States must be credited to their influence. In Europe, however, where the heat treatment of castings has remained undeveloped, high-silicon alloys such as "Silumin" and "Alpax" are used quite extensively.

The heat-treated 4 per cent copper alloy (195) had by this time attained a fair degree of popularity but was not entirely satisfactory, from a foundry viewpoint, for intricate castings. Experience with the silicon alloys suggested their use as a possible solution for some of these difficulties if a heat treatable composition could be found. Two alloys ultimately were selected, Nos. 355 and 356, having heat-treated properties approaching those of 195 alloy but better foundry characteristics.

In this brief history, which has been limited to sand casting alloys, only a few of the more important compositions have been mentioned. The sand casting business is a custom trade and has many special problems for which special alloys are employed, but the limited space prevents their description.

Alloys for Permanent Molds

Sand castings, however, do not constitute all of the aluminum castings business: Permanent mold castings are important. One of the first alloys used for permanent mold castings, then principally pistons, was the copper-iron-magnesium alloy (122); an alloy which remained the standard until recent years. The search for a better-wearing aluminum piston alloy of lighter weight and a lower coefficient of expansion led to the development of an alloy containing silicon, magnesium, nickel and copper (132). This alloy had satisfactory casting and mechanical properties and a 15 per cent lower coefficient of expansion, but was difficult to machine. The introduction of tungsten carbide cutting tools later solved this problem and 132, or "Lo-Ex", alloy now is used widely. The final successful utilization of this piston alloy was due in no small measure to the continued and persistent efforts of L. W. Kempf of the Aluminum Research Laboratories.

As a by-product of the development of casting alloys, two forging alloys were developed for special uses. One of these, 18S, resulted from modifications of 142 alloy while the other is a variation of 132 alloy. The latter, 32S, generally is used for the production of forged pistons.

Several of the more recent casting developments are in the aluminum-magnesium group of alloys. This type of material was investigated somewhat many years ago but was discarded as useless. Later, a series of aluminum-magnesium alloys (Magnalium) was developed and used to some extent in Europe but did not prove popular in this country. The alloys most recently exploited here contain from 4 to 10 per cent magnesium and all have a relatively high purity base. All have extremely high resistance to corrosion, while the 10 per cent magnesium alloy has unusually high mechanical properties, although special foundry technique is required to secure consistently good castings.

This article hardly can be completed without some reference to the most recent development in this field; that of free-cutting alloys. It represents the culmination of many years' effort but is so recent that its value can not be fully assessed. It is enough to say that the previous limitations of aluminum alloys for screw machine work have been removed by the new alloy 11S.

EDITORIAL COMMENT

(Continued from page A21)

undercarriages to stand rough landings were those of fair notch toughness values. Hoyt cites tractor experience and General Electric experience along the same lines. Then the fact became clear that the peculiarity of some materials in showing now a high, and now a low, value in room temperature notched tests was not due to innate cussedness of the test but to the material tested being in the temperature range of transition from a high to a low toughness, so that at higher or lower temperatures duplicates would check. Without any hullabaloo or any official concerted action, engineers began to demand impact data and metallurgists began to supply them, so that today no one thinks of describing a new alloy for structural uses without stating its impact properties. This attitude has spread all over in much the same spontaneous fashion as opposition to the "New Deal" has spread in the last two years. Everybody got wise to the true situation just about the same time.

A nice thing about the impact test is that it is a quick and easy one. Hence the cost of a few added tests, if by them we can get added information, does not lead to disgruntlement. When Hoyt points out that one needs both a narrow and a broad specimen, and perhaps tests on both sizes at some temperature below normal, in order to sieve out materials that might happen to show up all right on the standard test at room temperature, but are on the ragged edge.

Impact properties are like the individual with indigestion, when he's free from it he's pleasant as can be, when he has it, he's an awful grouch, and unless you meet him when he does have it, you'd never suspect that he could be grouchy. Older readers will also think of the similarity to the little girl with the curl. This fact, as pointed out by Hoyt, is becoming understood and no informed individual thinks that a 40 ft. lb. material is just twice as good as that with 20 ft. lbs.

The factors of ability to deform locally and to harden up but slowly on cold working as deformation proceeds, which Hoyt emphasizes as desirable for low notch-susceptibility are interesting in comparison with those necessary to good performance under repeated stress in the presence of stress-raisers, which are usually taken as ability to deform locally and to harden up rapidly on cold-working. Maybe when the notched bar problem gets fully cleared up, the stress distribution problem in fatigue will be, too, or possibly we many find that enough tests along both lines, and a proper correlation of them, will evaluate material for practical service under conditions in

(Continued on page 50)

Recent Developments Affecting the Testing Society's Specifications for Steel Castings—II

By R. A. BULL

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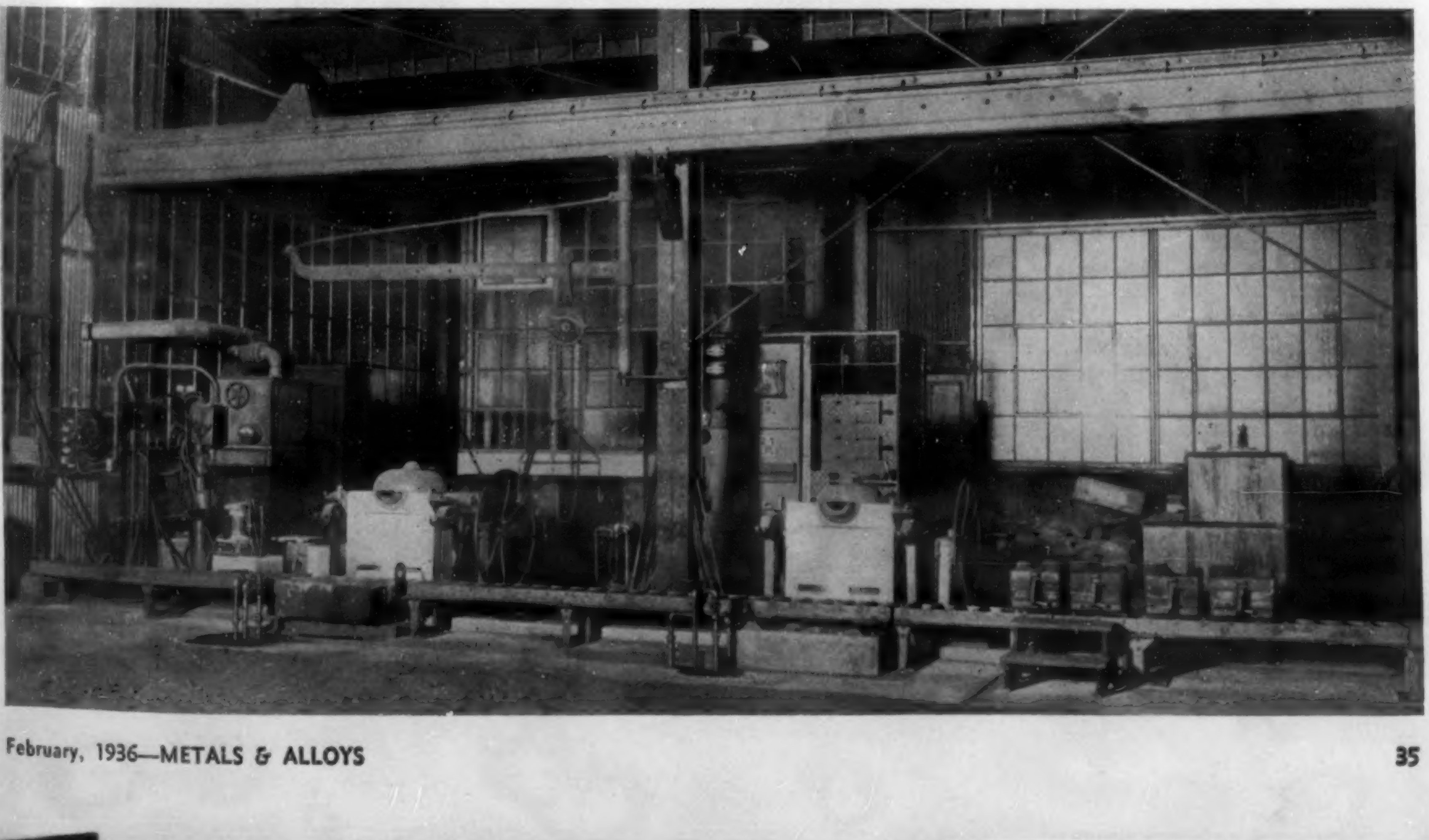
IN THE FIRST installment of this article, [METALS AND ALLOYS, January, 1936], reference was made to two problems presented in the recent efforts to modernize specifications for carbon steel castings. One of these problems has not been fully appreciated by those metallurgists who have not had opportunity to observe the varying conditions produced by the several applied methods of manufacturing test material in the steel foundry.

Consistently Developed Use of Separately Cast Coupons

Conventional specification clauses in the past have called for test coupons to be cast separately or to be cast attached to commercial steel castings. Some of the later specifications have prescribed (with discriminating justification) that test coupons shall be cast separately when the design of the ordered castings is such as to produce by coupon-attachment either an unsound condition of the coupon or an injury to the commercial casting. There are cast parts that afford suitable opportunity for feeding coupons that are directly attached thereto for their entire length, but at the expense of satisfactory properties in the affected locations of the purchased castings. Obviously it is ridiculous to assure the soundness of test material in any manner that might injure the commercial product by "bleeding" it to compensate for the natural contraction of the coupon-metal. The writer has seen what would have been sound castings ruined by effectively feeding coupons attached for their full length to the parts designed for service.

As this and other practical problems have become better understood by consumers, the practice of separately casting steel foundry test coupons has become increasingly preferred. It may be remarked here that only in the steel branch of the foundry industry is there followed today with any frequency the practice of determining metal properties by means of a test piece cast integrally with the commercial product. For many years it has been the custom to evaluate the metal for gray iron, malleable iron, and non-ferrous castings by means of test coupons cast independently.

High Frequency Induction Melting Equipment for Making Alloy Steel Castings. (Courtesy of Taylor-Wharton Iron & Steel Co.)



Equipment for Controlling Molding Sand Practice. (Courtesy of Sivyer Steel Casting Co.)

The latter practice has sound elements of accurate comparison in its favor. Everyone who knows much about the founding of metals realizes that the properties in a casting are dependent to a very large extent on the design of the piece. Considerable has been written on the influence of mass and such injurious design factors as sharp corners, marked inequalities in member-thickness, etc. Because of the relatively high degree of shrinkage or contraction that characterizes steel, good metallurgical design is even more to be desired for the production of steel castings than for the manufacture of parts cast from iron and certain other metals that contract to lesser extent than does steel.

Some Deficiencies Caused By Very Slow Cooling

Metallurgists know that the production of large crystals, dendrites, and segregation is materially facilitated by retarded cooling incidental to the solidification of large masses of steel. But it is not mass alone which, by slowing up the cooling rate, produces these undesirable results in the ordinary steel casting. The nature of the mold used to form a member of given thickness has a contributory influence on the time required for cooling. Obviously a green sand mold carrying the originally supplied amount of moisture (minus the small loss caused usually by evaporation) will exert a more rapid cooling effect on a given volume of liquid steel of given temperature and composition than will the same amount of molding sand that has been well baked. And the fact that more than member-thickness and sand condition are involved will be appreciated by visualizing the solidification of a cast plain slab 6 in. wide and 3 in. thick, and a cast channel 6 in. wide having all members 3 in. thick. It is obvious that, under comparable conditions of metal temperature and of molding sand, the slab will cool more rapidly than will portions of the channel. The cooling rates would differ to even greater extent if an H or a box section having member-thicknesses of 3 in. were substituted for the channel.

Of course it is the purpose of the designer and the foundryman to obtain, so far as possible in each member of most commercial steel castings, those properties that are inherent in the selected grade of metal, properly heat treated (as usually required) for a given purpose. And the main objective sought in prescribing physical test values is to assure the buyer that the metal is of satisfactory quality.

Unique Test Bar Requirement in New Specifications

It is now relevant to discuss the unique feature of Specifications A180 (miscellaneous carbon steel castings), issued in 1935. Their tensile requirements have been prescribed with manifested regard for the relationship between the method of manufacturing test material and the physical properties of the latter. It is provided that the test coupons shall be designed by the manufacturer; that they may be cast separately unless otherwise specified or agreed to between purchaser and manufacturer; and that when the test coupons are cast attached to a commercial casting, the manufacturer may select the location for the coupon and may provide for its attachment directly or by means of a runner. Thus it becomes the sole privilege of the foundryman to depart from the indicated paths of safe testing procedures, if he cares to take the chance.

The specifications contain a note stating, in effect, that lower combinations of physical properties than those characteristic of coupons, so made as to cool at moderate speed, are obtained when testing specimens from coupons attached for their entire length directly to massive casting members of such nature as to make the coupons cool very slowly. It is further explained that greatly retarded initial cooling develops a larger granular structure than that found in coupons of the customary kind, made as ribs on test pieces of keel block design; and that large grain size has an important influence on the properties of the steel in the "as-cast" condition, and on the extent to which such properties may be affected by an applied heat treatment.

To prevent misunderstanding, it should be explained that no deceptive motive has been responsible for the fact that prior to 1935, A.S.T.M. specifications for miscellaneous steel castings contained no language indicating that test values are dependent partly on the factor that has been mentioned. The serious technical need for differentiation developed a few years ago, emphasizing a condition which had been recognized more or less academically by many producers and some consumers. It would now be improper in any way to disregard the fact that differing results may be obtained from one heat of foundry steel, depending on the method of producing the test material. And of course it would be reprehensible to convey the idea that the physical properties in suitably produced test coupons are substantially like those that might be found in all portions of most commercial castings made in the same heats.

The designing engineer who has had much experience is well aware of the fact last mentioned. The average mechanical engineer may not have realized the extent of mass-effect which has been recently emphasized. The inexperienced designer whose attention is drawn to the matter might reason that the irreducible amount of resistance to anticipated stress in a vital member of one of his castings could only be definitely determined after destroying the casting for the purpose of testing it. Such questions as these might then be raised: What may the engineer do to assure himself regarding the needed stress resistance of the material purchased? What satisfactory purpose is served by resorting solely to tests of material made under conditions that more nearly approach the metallurgical ideal than can be provided in all members of the part to be used in service?

When the job is sufficiently important to justify destructive testing as an exploratory procedure before beginning on volume production in the foundry (supplementing one or more of the valuable non-destructive methods of appraisal), test specimens may be taken from each of the desired number of important locations in pilot castings. In this way a very reasonable idea is obtainable regarding the stress resistance to be expected in all castings from the pattern under consideration, provided that they are manufactured under proper conditions of control and are intelligently inspected. (It may be surmised logically that such practical measures, which are quite common on large production jobs, were taken in the production of approximately 2,000,000 cast metal alloy crankshafts that have been successfully used in automobiles since 1933.)

It is far beyond the attainable limits of excellent foundry practice to develop such physical properties in every portion of each of many castings as would equal the properties in a coupon produced under nearly ideal conditions, poured from the same heat of steel. But this circumstance, when considered in connection with all phases of metal part manufacture, provides no basis for lack of confidence in the product of the foundry. The processing methods used for making every kind of metal part influence the degree of stress resistance in portions of the members; some enormously, others slightly. Of course that is one reason why designing engineers use factors of safety.

Requirements Needed for Evaluating Massive Full Annealed Castings

In a minority of cases (which nevertheless are commercially important because of the service rendered by the parts concerned), the common practice has been to attach test coupons for their entire length and width directly to thick members of certain steel castings that are of such large proportions as generally to be subjected to a full annealing treatment of much longer duration than the customary one for such castings as are full annealed in preference to normalizing. Bridge castings are among those in the category first mentioned.

The personnel of the special committee that developed Specifications A180 included individuals who collectively were familiar with every variety of steel casting that is now produced; including pieces ranging in weight from a couple of ounces to 200 tons, in over-all size from an inch or two to as much as 70 ft., and in member-thickness from $\frac{1}{4}$ in. to several feet. Under these circumstances the committee considered its job as being incomplete, when Specifications A180 were developed in their present form.

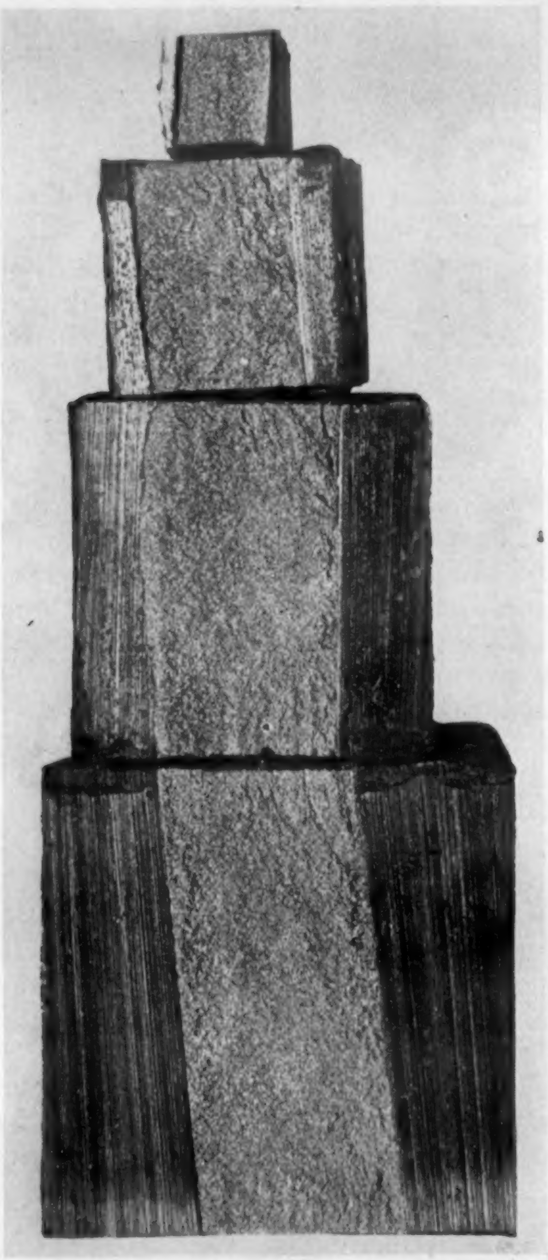
Much study has been given to the yet unsatisfied needs of those engineers who believe that certain carbon steel castings (usually because of massive sections but sometimes because of intended application, without the incidental feature of great member-thickness) should have a prolonged "soak" at annealing temperature and a subsequent very gradual return to room temperature. Most of the engineers who are specially interested in such castings prefer that their test coupons have full-length attachment to the purchased material throughout heat treatment.

Test specimens made from coupons thus attached to massive members and full annealed in the manner just described are characterized by a combination of tensile properties which is materially lower than the combination developed by the normalizing treatment usually given to carbon steel castings, and considerably lower than the combination developed by a full annealing treatment completely carried out for a period less than 12 hr. on the test specimen from a coupon molded under conditions permitting it to cool rather quickly. The greatly retarded initial cooling, because of the coarse structure thereby produced, calls for more heat to develop granular refinement. And the softening effect is, to considerable extent, proportional to the amount of heat applied before starting to lower the maximum temperature.

It is not assumed that the above statements convey new information to the average reader of Metals & Alloys. The purpose of the comments is to demonstrate the insuperable difficulty of establishing an acceptability standard that would, with the same degree of tolerance, fit all cases of test specimens supposedly representing full annealed castings. Prolonged consideration has resulted in no feasible plan of defining or classifying the purchased material on the basis of thickness of predominant members or of specified minimum time of full annealing cycle.

Heating Small Alloy Steel Castings to Meet Exacting Requirements (Courtesy of Sivyer Steel Castings Co.)

It may be found advisable merely to establish two sets of required tensile properties; one for normalized material, the other for full annealed material presumed to have such massiveness as might prompt the cautious buyer to rely on test data resulting from a very long "soak" and a greatly retarded cooling within the annealer. If specifications A 180 ultimately are revised in this manner, probably many engineers will be surprised to see the differences in the obtained



Cast Steel Blocks Made to Ascertain Effect Heat Treatment As Influenced by Mass. (Courtesy by Michigan Steel Casting Co.)

physical properties. This is apt to increase the popularity of normalized material, when the castings have members that are not extraordinarily thick. And it may be mentioned here that the huge majority of carbon steel castings are of such nature as to make normalizing preferable to full annealing, for attaining maximum stress resistance with minimum weight.

Turbine and certain other castings for ships are in the thin-member category of material frequently required to be full annealed, while huge castings for bridges and dams are in the thick-member category. It will be evident that the term "full annealing," while it means oven cooling as an essential detail, conveys different ideas to different people. A cycle of less than 12 hr. may be as beneficial in one case as the cycle of two weeks in another case. When cross sections of main members of different castings may actually vary by a ratio of one to two hundred, it is out of the question accurately to standardize any factor which is partially dependent on cooling speed that is not artificially accelerated.

Security Dependent On Practical Measures Easily Adopted

Considerable work that has been done to determine the influence of high temperatures applied for extended periods of time in causing steel to "creep," indicates that the heat treatment given the metal may have a greater effect on its stability at high temperature, than that produced by an appreciable difference in the content of some important element of the composition. Perhaps the effect of heat treatment on granular structure is not unrelated to the influence of cooling rate prevailing in the casting that has just been poured. The significance of associating the degree of high temperature *with the time consumed in its application* becomes emphasized from several standpoints in considering the steel casting; when it is formed originally, when it is subjected to regulated heat for adapting its properties to anticipated stresses at normal temperatures, and of course when (after any needed preparatory treatment) it is placed in high temperature service. A better appreciation of some of these conditions might prompt some persons to conclude that chemical composition has been credited in some quarters with more influence than it exerts.

The recognition that has been given in recently issued specifications to the effects of cooling rate on the product of the steel foundry might happily cause improvement in designing practice, through the development of sections whose calculated resistance to stresses should be measured discriminatingly on member-thickness. The influence of mass on the duration of time for natural initial cooling and for subsequently regulated cooling cannot intelligently be disregarded. Practical problems of this kind become more important as the demand for light-weight equipment increases. Certainly there is now great need for designers to be guided by the readily observed demonstrations of metallurgical principles that govern commercial manufacture.

Perhaps this discussion of means for determining physical properties in steel castings may be helpfully concluded by adding a few comments on what might be termed the idealistic nature of some advocated methods of producing test material.

The principal objective in making chemical and physical tests on laboratory specimens of any metal is to determine the properties that are characteristic of the material. Admittedly an engineer may deceive himself by assuming that the stress resistance in a vital member of a casting satisfactorily compares with that indicated by testing material formed under such conditions as to show what the metal can do when given its best chance to perform.

While it can be said truthfully of many cases that every member of a typical cast or wrought part of any metal from a new design represents a separate engineering problem, it is unlikely that there is great difference in the stress resistance of most of the intelligently formed members of steel castings poured from one heat. This does not alter the fact that in many castings that give satisfactory service, there are individual members so shaped and/or connected as to materially lower the resistance of those portions to mechanical stresses, compared with the potential resistance of the steel. Obviously there are a great many degrees of reduced stress resistance which are neces-

(Continued on page 43)

NOTCHED BAR TESTING—II

By S. L. HOYT

Director of Metallurgical Research, A. O. Smith Corp., Milwaukee

Continued from the January Issue

The Notch Effect

I HAVE STATED certain opinions relating to the notched bar test and what it is capable of doing, but without bringing proof of the correctness of those opinions. This seemed to be worth while doing even though it did no more than give an outline of the general thesis which will be developed. I have indicated that such proof will require a detailed consideration of individual features of the test and of the notch effect in particular.

Now, lest there be a misconception here, it should be noted that the "notch effect" occurs in all materials; it is only certain of them which, though normally ductile, exhibit the peculiarity of "notch brittleness." It is the direct object of the notched bar test to detect such materials and avoid their use in service. Furthermore, the notch effect may be harmful even in notch tough materials and it should be part of good engineering practice to eliminate the effect and produce a "stream line" and axial flow of stress from one cross section to the other.

While a more precise statement of the notch effect will be made in a later section, one of the best known features is the concentration of stress and strain at the apex of the notch. This effect is well known from the literature and has been shown with particular clarity by the work of Professor Coker and others by the use of polarized light on transparent models. For the present purpose I am showing how stress concentrates at a circumferential notch in a bar of steel. This is shown by Fig. 1 which is taken from some early work of Preuss. It shows that, though the average stress on the cross section at the base of the notch is only 750 kg. per sq. cm., the longitudinal or normal stress right at the notch rises to 1602 kg. per sq. cm. and 1859 kg. per sq. cm. in these two cases. The variation in stress over the whole cross section is shown by the ordinates raised to the curve. Such a concentration of stress need not necessarily be dangerous, for steel has a very high resistance to cleavage in the normal direction and can sustain higher loads of this type than we are accustomed to think of as safe.

Other important features of the notch effect are brought out if a sufficiently high load is applied to produce plastic flow. The ordinary plain test bar deforms uniformly over its whole length. This deformation is due to shearing stresses at 45 deg. to the axis of the bar. Even though this stress has a magnitude of only one-half of the normal stress which tends to cleave the bar at right angles to the axis, the resistance to flow is so low in ductile metals that plastic flow sets in. A circumferential notch has the effect of reducing the area which supports the normal stresses. This results in a modification of the stress at the notched area such that, as the effect of the notch increases, the tendency to deform plastically decreases and the tendency to cleave increases. Kuntze has shown recently that the notch effect can be made severe enough almost completely to inhibit plastic flow so that fracture occurs by almost pure cleavage. If we now recall that the normal stress at the base of the notch is really well above the average stress, it becomes clear that the presence of a notch has a pronounced tendency to open up the notch as a crack at the notched section before any material deformation occurs in the vicinity of the notch. These points can be suitably illustrated by some tests of Ludwik and Scheu which will be briefly reviewed.

Ludwik and Scheu prepared a series of test bars in which the notch effect varied from zero in the first one to a maximum in the last. These are illustrated in Fig. 2. These test bars were all pulled in a tensile testing machine with the results as given in Table 1.

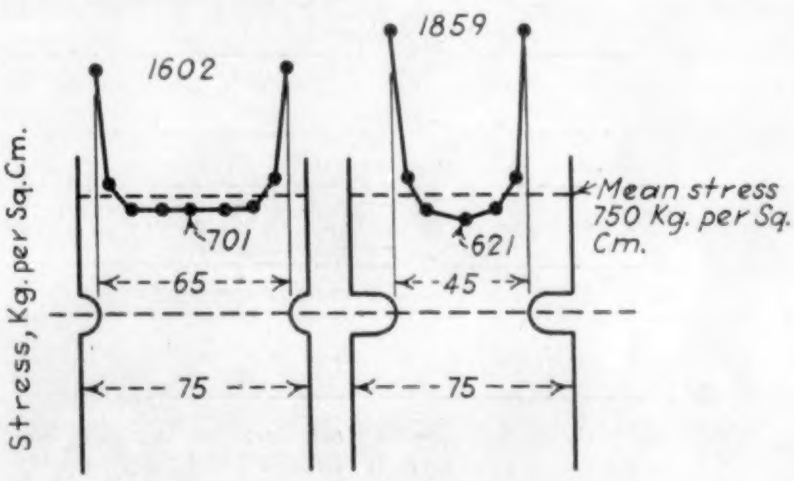


Fig. 1. Stress Concentration at Notch. (Dimensions are in millimeters. Radius of notches = 5 mm.)

The diameter of the bar at the base of the notch was the same in all cases and was equal to the diameter of the straight cylindrical bar,—10 mm.

Table 1.—The Notch Effect in Tensile Tests. Ludwik and Scheu.

Bar	Tens. Str., kg. per sq. mm.	Elong., per cent	Red. of Area, per cent	Effect. Elong. $\frac{RA}{1-RA}$ *	Work of Rupture, kg. × cm.
a	39.6	35.7	69.0	233	10,147
b	43.8	7.5	64.6	182.5	2,281
c	46.2	5.6	58.2	139	1,772
d	51.6	3.6	42.7	74.5	1,232
e	59.2	2.3	32.8	49	905
f	64.4	1.5	22.5	29.1	710

* Estimated maximum effective elongation in per cent.

The figures in the first three columns show that the measured strength and ductility are materially altered by the notch and that the effect increases as the angle of the notch decreases. The most notable change is that of the figure for elongation. Reverting to what was said earlier about the effect of an impact, it is clear that bar "f" would absorb far less energy in rup-

turing than bar "a" would, for in bar "f" the volume of metal affected is materially less than in bar "a." The greater stress carrying capacity of bar "f" is not enough to compensate. The actual decrease in the work of rupture is given by the figures in the last column. These figures bring out the simple mechanical effect of a notch on the behavior of a material in the tensile test. We may confidently predict that the notch will weaken the bar in impact in the same way.

Additional familiar examples of the notch effect are given by the scratch on a glass rod if it is to be broken off, or the nick made in a bar of steel for the same purpose. Shatter cracks and transverse fissures in steel rails and internal checks in hardened steel must also produce stress concentrations and may be regarded as internal notches. An examination of glass with polarized light shows stress concentrations around "seeds" and presumably the same situation exists around foreign inclusions in steel. In fact, in many quarters, foreign inclusions have a bad reputation as "stress raisers." Scratches and surface imperfections

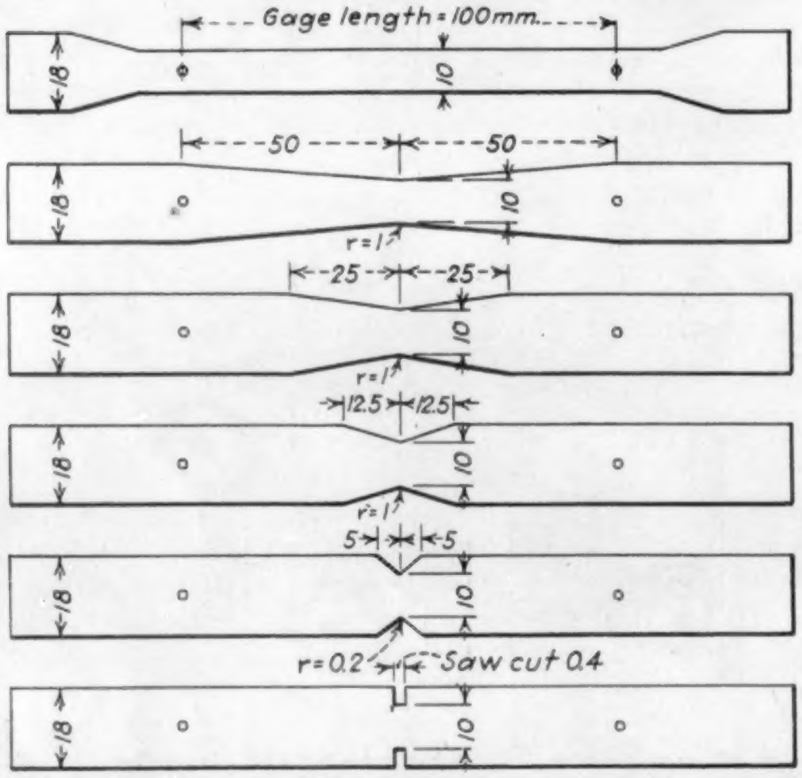


Fig. 2. Notched Cylindrical Tensile Test Bars—in Section. (Dimensions are in millimeters). Ludwik and Scheu.

are also notches which reduce the fatigue strength of a bar of steel.

During super-elastic loading two different types of behavior have been observed with material of the normally ductile type. If a metal is of the notch sensitive type it breaks sharply by simple extension of the notch as a crack. The crack thus formed becomes a particularly sharp notch and greatly aggravates a bad condition. If the metal is not notch sensitive (to the particular notch effect) the metal at the base of the notch flows and reduces the notch effect by increasing the radius of the notch though of course the major geometrical features remain unaltered. Well-made steel and most non-ferrous metals are of this latter type.

Use of the Notch Effect in Testing Steel

We have now described the effect of a notch in concentrating stresses and in accentuating the tendency for a bar to break with low elongation and small energy absorption. I hope I have made it clear that this is a "notch" effect and not an "impact" effect.

The simplest type of notched bar test is the notched tensile test which we have already discussed. At one time this test was advocated for general use to secure a better idea of the true strength of the material than is given by the tensile test on plain bars. While the point of view was sound enough for some purposes, the results were of minor significance technically. Inasmuch as it is the work of rupture that furnishes the desired criterion of toughness a more convenient method to use is that of breaking the bar in impact and measuring the energy absorbed in doing so. This was the method of Russel who studied the behavior of cast iron in impact many years ago. In general the impact test gives about the same results as the static test, though for most materials the energy absorption is somewhat greater.[6] The difference here is about the same as was observed for plain bars broken statically and in impact. This method of carrying out the notched bar test appears to have advantages and I understand that one prominent laboratory, at the Watertown Arsenal, has adopted it as standard. The method developed by Kuntze for machining a notch on a cylindrical bar should find a useful application here.

Coming to the standard transverse, notched bar, impact test we shall not attempt to trace its history, instructive as that would be. Henry Le Chatelier has described its birth and evolution in France in a very interesting paper[7] while Fettweiss has gone critically into all phases of notched bar testing very thoroughly.[8] I know of no such thorough reviews in English. The early work described at meetings of the International Association for Testing Materials has also been mentioned. The more important tests which came out of that early work were those of Barba, Fremont, Barba and LeBlant, Vanderheym, Guillery, Charpy and Heyn. Of these the Charpy test has survived as the one best adapted to accurate measurements of the energy absorbed in breaking notched bars while the test of Heyn is undoubtedly the simplest method of detecting notch sensitive material. Also at an early date the Izod test was introduced into England and it now ranks with the Charpy test in this country as a standard procedure, though we have no truly standard test in the usual sense. These tests are so well known that they need not be described.

There are some unusual circumstances surrounding notched bar testing which need to be ironed out before this test will be on a satisfactory basis in this country. At present we select a testing procedure, break a few bars to secure checks, and then rate the material according to the impact value. If we wish to impose a more severe requirement for notch toughness, we simply set up the acceptance limit. This principle is perfectly sound in general, but, oddly enough, it does not necessarily, and may actually not, hold for notched bar testing.

For example, some materials are definitely tough in the plain or slightly notched condition and yet are quite brittle if the notch effect is more pronounced. In other words a high impact value with one notch does not of necessity guarantee that the metal will be tough under all circumstances. We can readily visualize two materials whose order of impact values will reverse on changing the severity of the notch effect. This quantitative evaluation of toughness in a perfectly arbitrary test is not without the serious psychological defect of suggesting that a definite property has been measured by the energy absorption. We should remember that we ascertain a certain technological behavior by this test and that we do not measure a material constant. This is inherent in the test as it is now constituted and our safe guide comes from an un-

derstanding of what we may term the "variables" of notched bar testing.

Variables in Notched Bar Testing

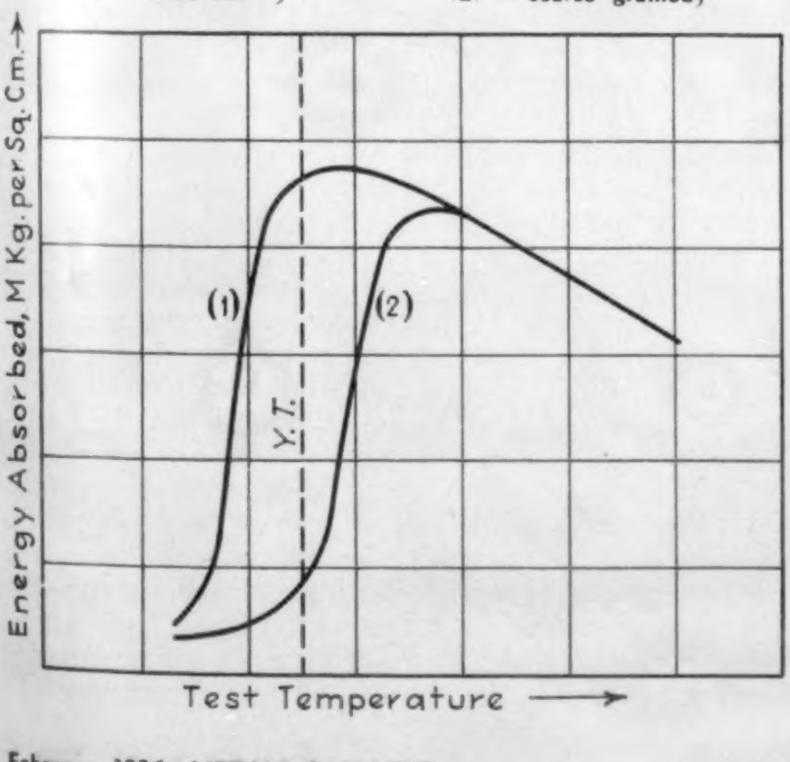
In the early work on the notched bar test, it was recognized that a fixed routine should be adhered to. Among other things the effects of all these variable factors were ascertained for the purpose of establishing a suitable routine. These variables can be divided into two groups, those relating to the geometry of the test bar, and those relating to the external conditions of the test.

Two of the first group of variables are the size and shape of the test bar. Out of this work the square bar has survived as the best shape, though the size is not universally the same. The work of the German committee which was reported by Ehrensberger indicated that the large 30-mm. bar gave results which correlated best with common experience. In this and other countries the small 10-mm. bar is used for both Charpy and Izod tests, while more recently the 10-mm. bar has also been introduced into Germany. On the whole it appears that the small bar is capable of giving good results though, if it is to be as satisfactory as the large bar, the notch design must be carefully selected. Experiments on the width of the bar showed that narrow bars were not capable of making the proper distinctions between materials of different toughness because the restriction at the notch was not sufficient to produce the necessary notch effect. This was felt particularly with the tougher steels. On this account the square bar was selected as being better adapted universally to notched bar testing. Sometimes a round bar is used in the Izod test but this shape does not appear to be suited to the test.

The design of the notch was found to be of considerable importance, as might be supposed. In brief, the smaller the radius of the notch, the lower the energy absorption was found to be, though the tougher steels were less sensitive than the more brittle steels. This was particularly true of properly heat-treated steels which were less sensitive to the sharper notches than the coarser over-heated steels were. The angle of the notch came in the same category as a variable and the sharper notches gave lower impact values. This was again a more important variable with the

Fig. 3. Test Temperature

(1) = narrow bar } or (1) = fine grained }
(2) = wide bar } or (2) = coarse grained }



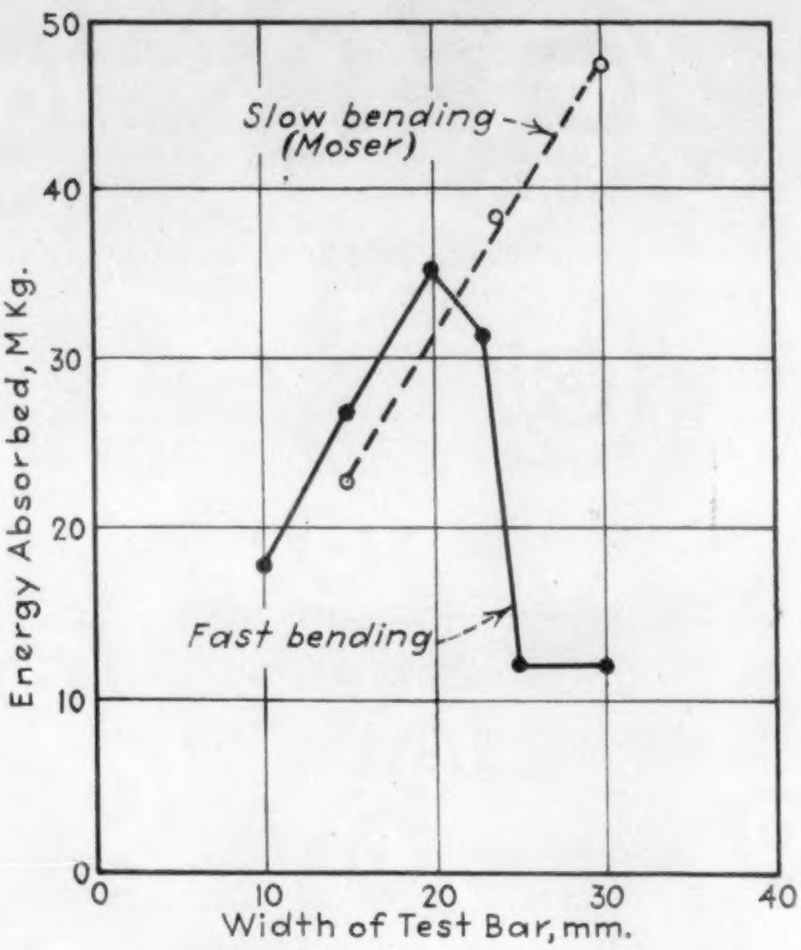


Fig. 4. Height of Test Bar = 30 mm. (Moser)

more brittle steels than with the tougher steels. The depth of the notch was likewise found to be an important variable. With the first increase in depth, the impact value was found to decrease rapidly and then to remain rather constant with further increase in depth. It will probably not be surprising that the law of proportional resistances is not obeyed in this field, as various experimenters have observed.

The group of variables which we have just considered includes the shape and size of the bar, the width of the bar, the radius of the notch, the depth of the notch, the angle of the notch, and the area at the base of the notch. Two observations stand out as being of special significance: The impact values depend very definitely on these factors and the effect is materially greater for notch sensitive steels than it is for the tougher steels. The second group of important variables includes the external testing conditions, the first being the striking velocity and the second the test temperature.

The striking velocity was found to have little effect on many steels within the usual limits of impact testing machines. The trend with the tougher steels was towards higher impact values as the velocity increased and Hadfield and Main report that a well made and properly heat-treated steel remained tough even at bullet velocities of 600 meters per second.[9] So it appears that really tough steels are not adversely affected by high velocities. Steels which tend more to notch brittleness are apt to be adversely affected and it is conceivable that a material broken statically in the Humfrey machine might show a tough behavior and yet be brittle when broken in an impact testing machine, though such instances are undoubtedly rare. On the whole the effect of striking velocity has not been as thoroughly investigated as would appear to be warranted.

Temperature has been found to be of particular significance in notched bar testing because the impact value of some steels varies very rapidly at about

room temperature and also because this variation is generally accompanied by a large spread in results obtained from similar samples. With a drop in temperature of but 80 deg. C. the impact value can fall off over 75 per cent. Room temperature is frequently a very inappropriate test temperature for use to get good check results. On the other hand a wide spread in results becomes a valuable index to metal quality. (It may be of interest here to note that the four com-

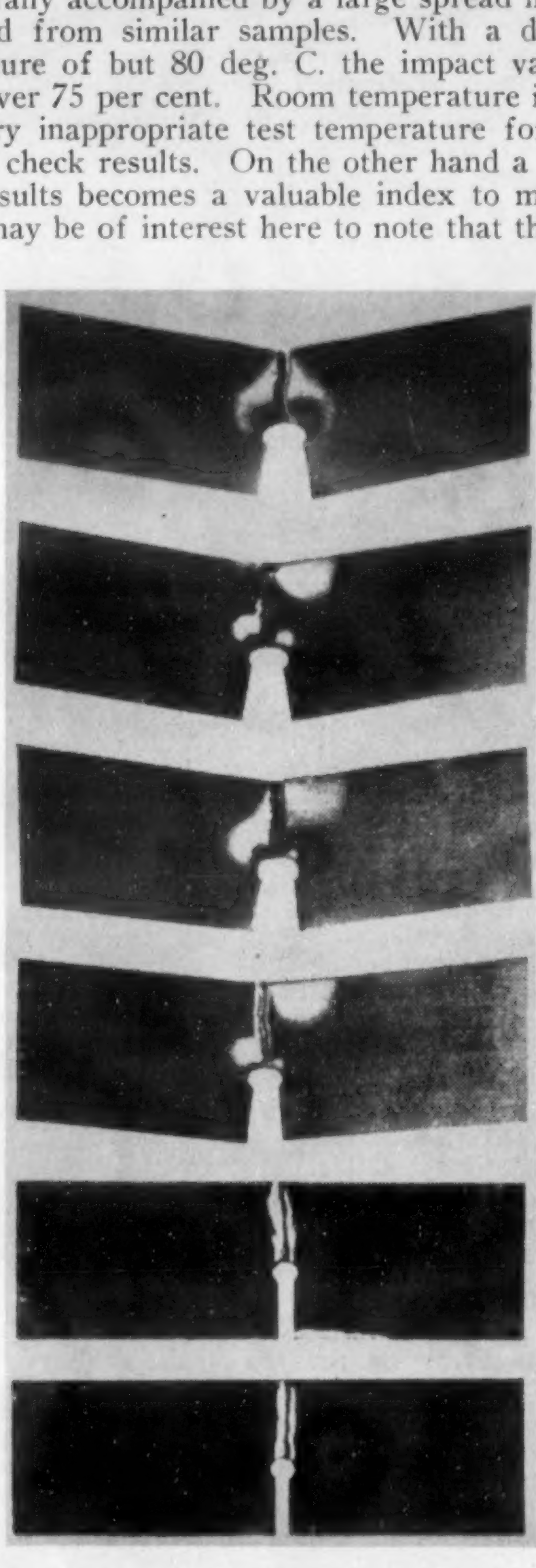


Fig. 5. Deformation of Bars of Different Widths. The bar height is 3 cm. in all cases, and the width is given in cm. Brittle fracture begins at 2.5 cm. (Moser)

mon tensile properties are scarcely affected by this change in temperature.) One reference should suffice as a specific example of the effect. Wrought iron of good quality has a good name for being a tough and dependable material and has long seen service as welded chains and the like. The behavior of wrought iron at various temperatures was recently studied by Gough and Murphy and they found that it did not develop brittleness at sub-zero temperatures even though chilled to —78 deg. C. when tested in the plain condition. When notched, it developed marked brittleness at about room temperature.[10] In that respect wrought iron resembled many of the mild steels of commerce, though the latter vary markedly in the way temperature affects their notched behavior. If tested a little above room temperature, coarse grains or temper brittle and other brittle types are equally as tough as the common tough types of steel. If tested a little below room temperature nearly all of these steels are brittle. A good example of this effect is shown in Fig. 3. Increasing the grain size had the effect of raising the temperature at which the sharp break in impact values came but otherwise had no effect on the values proper.

Effect of Combined Variables

More recently additional work has been done on these variables, though the later work was more detailed and also took the significant direction of getting the effects of the variables in combination. The work was done largely at Krupp's in Essen and dealt particularly with variable width bars and with the effects of varying the test temperature and the striking velocity.

Following Baumann, Stribeck was the first to establish the effect which the width of the test bar may have on the impact value. In general three different zones are recognized as the width of the test bar increases. At first the impact value increases in direct proportion to the width. Above this range, a zone of spread is encountered over which the values are high or low, or possibly intermediate. With still wider bars the impact values are uniformly low, though different steels would show different quantitative behavior.

At the Krupp Testing Laboratory, Moser confirmed the effect of increasing the width of the test bar as may be seen by reference to Fig. 4. In addition, he showed that the amount of energy absorbed per unit volume of deformed metal remained constant, in spite of the drop in impact value. He held this value to be a material constant, which he termed the "work constant per unit volume." On this basis the impact value of a given test bar depends on the amount of metal deformed. Even though the wide bar gave the appearance of being much stronger than the narrow bar, the effect of the notch was such that only a small volume of metal could be utilized in absorbing the energy of the blow. This effect is shown by Fig. 5.

Upon testing different materials with bars of different widths, it became apparent that some were better able than others to "transmit strain" from the base of the notch to the surrounding metal. These metals were "fast" or "slow" according to what Moser called their "velocity of strain propagation." This was held to be a second material constant. By a second series of tests he found that the width at which the drop in impact value came was somewhat greater when a lower striking velocity was used. (See Fig. 4.) The lower velocity permitted the "slower" metal to deform and absorb energy, or that was the interpretation put on it at the time.[11]

At about the same time Mailänder, also of Krupp, conducted a rather comprehensive series of tests on bars of different widths which included the effects of different striking velocities and different temperatures. By combining these variables he found that the width at which the drop in values comes is greater as the test temperature increases and as the striking velocity decreases. Fig. 3 shows that wide bars develop temperature sensitivity at higher temperatures than narrow bars do. Again, the real narrow bars were relatively insensitive to the effects of striking velocity and temperature while the wide bars were definitely sensitive to both variables. In all cases the character of the fracture followed the impact values with excellent correlation. In other words those bars which broke with a high energy absorption per unit cross sectional area also broke with a fibrous fracture while

those bars which broke with a low energy absorption also broke with a crystalline fracture.

Other tests were run in which the notched bars were broken statically with apparatus for determining the stress-strain diagram. At —20 deg. C. the series showed the drop in impact value at the 20-mm. width. This bar and those which were wider gave diagrams which showed that the stress rose rapidly to a maximum, at which point the bar broke suddenly with a brittle fracture. The narrower bars, or in general those which broke with a fibrous fracture, gave diagrams which showed an increase in stress to a maximum but this time the deformation at the maximum was sufficient to account for about one-half of the energy absorption. Beyond this point the bar continued to deform but the stress fell off slowly to zero. When the maximum stress indicated on the diagrams was followed, it was found that it increased uniformly throughout the whole series, despite the drop in impact value. This showed that the reason for the falling off in impact value was due to the inability of the wider bars to deform, thus confirming Moser. It was likewise observed that the maximum stress developed at —20 deg. C. was greater than at 20 deg. C. for the same width bar.

Additional illuminating observations were noted when the notch was changed from the V type to the key hole type. This had the effect of lessening the notch effect and, in turn, of shifting the zone of spread to wider bars and to lower temperatures. With a constant notch the same shift was accomplished by refining the structure by heat treatment which lowered the notch sensitivity.

The work done at Krupp's by Moser and Mailänder created a new interest among those who were concerned with notched bar testing, particularly those who were seeking an explanation of the intricacies of notch behavior. As we shall presently see, it started people anew to thinking about the meaning of the test. New experimental work was planned and done and new ideas were introduced; even though Moser's original concepts have not survived, his contribution was of major importance. Moser also introduced a modification in testing procedure which is still a worthwhile thing to do. As a special method for determining whether a steel was "fast" or "slow" he broke two 30-mm. test bars of different widths, 15 mm. and 30 mm. Unless the full width bar gave about double the value of the half width bar, the metal was "slow," while "speed" could be expressed as a percentage.

On the whole a discussion of the effects of the variables of notched bar testing gives a rather confused picture. When we recall that a change from tough to brittle behavior can occur as any one of these variables changes and that service conditions are apt to combine these variables in the most heterogeneous fashion, we need not wonder that discrepancies are met in testing nor that many test results appear not to correlate fully with service behavior. It is not quite as simple as merely breaking a test bar, noting the energy absorption, and equating that value to the toughness.

At this point I should like to see if these experimental findings cannot be simplified or better coordinated into more useful form. First of all we can divide the variables into two groups, (1) those which affect the notch effect to which the material is subjected in the test, and (2) those which affect the inherent notch toughness of the material itself. In the first group I would place those variables which have to do with the geometry of the bar and the notch, like the width of the bar, angle of the notch, radius of the notch, and depth of the notch. We shall want to remember later that if we wish to make use of a variable which will subject the test material to a more or less intense notch effect, we can select one from this group. In the second group I would place the test temperature and the striking velocity. Many steels are sensitive to both of these variables and, in testing, it may become desirable to take this into account. Later on when we are discussing methods for conducting notched bar tests, an effort will be made to utilize these findings to set up a rational procedure. Now let us turn to the hypothesis of Ludwik which seeks to give a rational account of notch behavior.

(To be continued)

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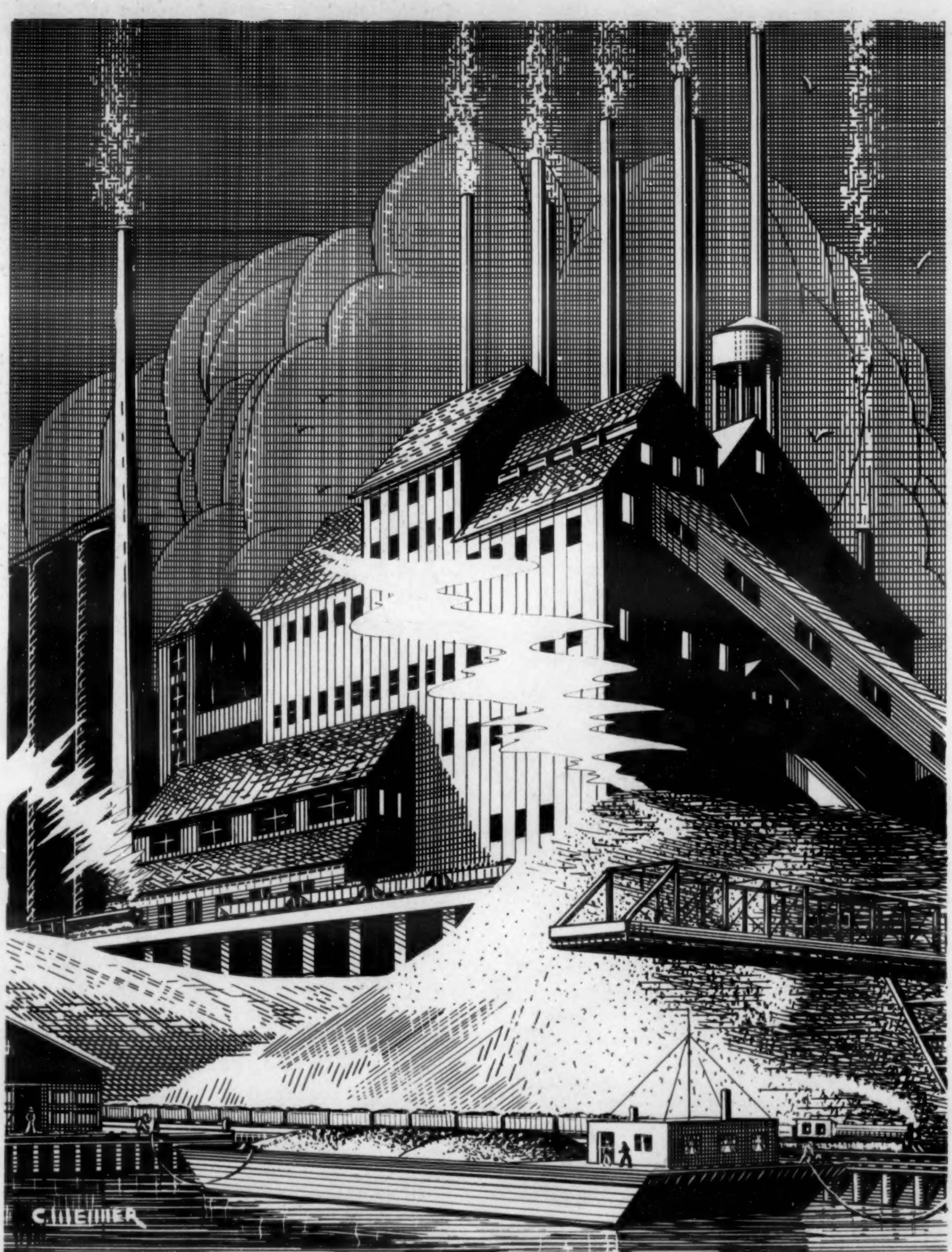
(Continued from page 38)

sitated by service and are governed by design. It becomes the most practical procedure to use such a skillfully produced acceptance standard as will permit accurate comparisons and will indicate the properties that can be expected of the metal when it is not subjected to handicaps of varying significance.

The experience of those who have used millions of tons of steel castings demonstrates the feasibility of relying with confidence on four factors: The adoption of metallurgically good casting design; the selection of the proper grade of steel; general and specific inquiry regarding the dependability of available sources of supply; and data obtained from laboratory tests on samples produced by a method that is known to be well adapted to all susceptible characteristics of the metal which may significantly affect serviceability for the intended application. When these things are done, the experience of the buyer is most unlikely to cause any regret.

(To be concluded)



Drawing by Charles Perry Weimer

INDUSTRY

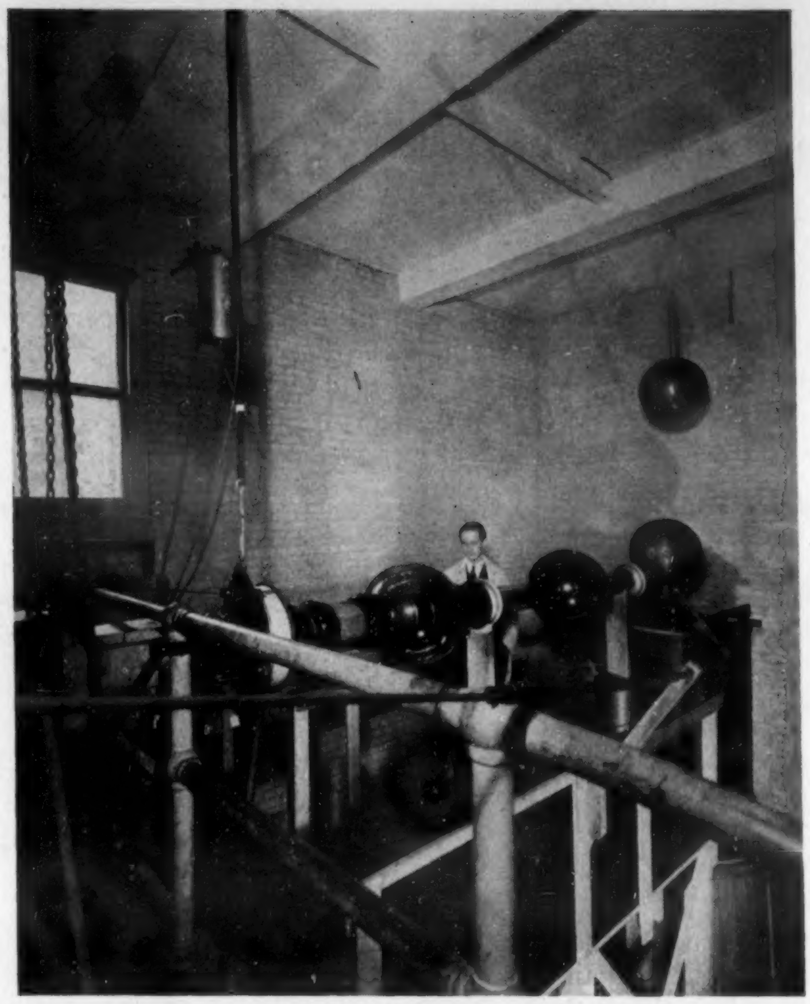
The Plant

INDUSTRIAL X-RAYS

An Introduction to the Physics of the Science

By ROBERT C. WOODS

Consulting Physicist, Old Lyme, Conn.



The 900,000 Volt X-Ray Tube Used at Memorial Hospital, New York, N. Y.

WHILE PLANT ENGINEERS and superintendents are by no means strangers to the fundamental facts of testing metal products by X-ray, a large number of them are perfectly frank in confessing to rather hazy ideas about how the penetrating radiation actually works. Show the engineer an X-ray picture of a flaw in a weld or casting, and his first remark is: "Yes, I see the flaw, but just how does the X-ray make it show up on the film?" This is not mere curiosity. The engineer has in the back of his mind a dozen tests of various types he might make, and he must know precisely how the X-ray acts before he can decide for or against using it. The engineer's hazy knowledge of the X-ray is probably due to the fact that at the present time practically all of the literature published on the subject of industrial X-ray work, except in books, takes it for granted that the reader is already conversant with the "whys and wherefores" of the matter. To most of those men who are too busy to delve into volumes on physics or dig back into past issues of technical publications, this has an effect very much like entering a theatre in the middle of a second act.

This article, therefore, is an attempt to answer, in as brief and as non-technical a manner as possible, some of the many questions which the author has been asked by engineers and production men in various manufacturing plants. There is no intention here of covering the entire field of industrial X-ray work or of introducing any new material.

Production of X-Rays

PERHAPS the easiest path to the understanding of this subject will start with the source of X-rays as produced by man-made methods, and will stress only the more important factors relating to X-ray production.

An average X-ray machine works along the lines of the following description: An incoming electrical line (220 volts AC) is fed into a step-up transformer which induces in its secondary coils the desired high voltage. Although this potential may run as high as the 1,000,000 volts used in some modern X-ray treatment tubes, the general range in industrial work is from 60,000 to 200,000 volts. Before applying high tension power to the X-ray tube, it is necessary to change the current from an alternating to a direct, or at least a uni-directional one, by means of a mechanical or vacuum tube rectifier.

The X-ray tube itself is a very highly evacuated glass bulb containing a spiral wire filament and a tungsten target.

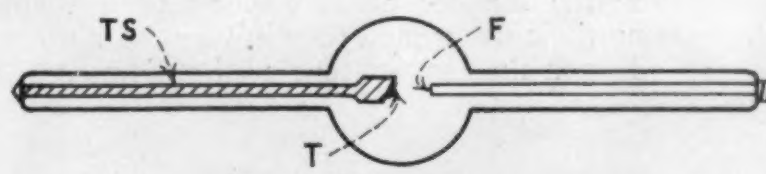


Fig 1.

In Fig. I, Ts, the target support, is a rod or arm made of molybdenum into the end of which is pressed a small button of tungsten, the target T. Directly opposite the center of the target is the thoriated spiral wire filament F, held rigid by the metal support shown. The only two things necessary to generate X-rays in this tube are a source of free electrons and a high potential.

It is a well-known fact that there are always large numbers of electrons in continual motion on and near

the surface of all matter, but at normal temperatures there are bonds present which seldom allow the electron much chance to roam. As the temperature of the material is raised, however, these bonds become weaker and weaker until, as in the case of incandescent metals, there is a cloud of electrons hovering around in the neighborhood of the surface.

This phenomenon is used to produce from the heated wire filament a source of electrons floating about more or less freely in the space between the filament and the target. As soon, however, as the

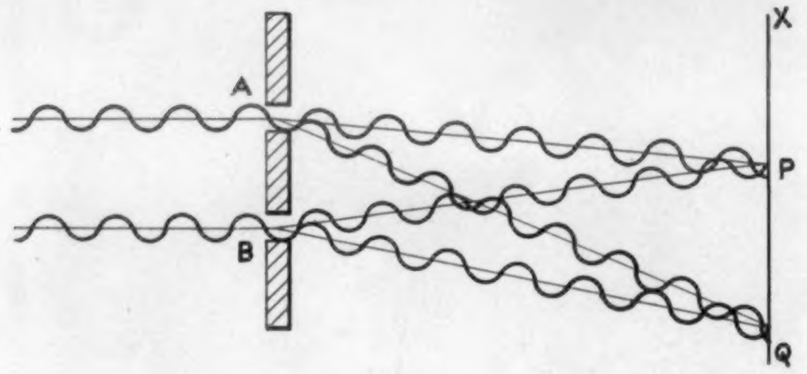


Fig 2.

high voltage is applied across the tube, an end is put to the aimlessness of the electrons and they are literally hurled against the target at terrific speed.

When these flying electrons strike the target, some are slowed down by the force of the field within the tungsten atoms, and others are stopped outright by collision with an electron in one of the atom-orbits. In some instances there is only a mild disturbance brought about and in others there is an actual rearrangement of the electrons within the atoms of the target; but in any case energy is given off by the tungsten in the form of radiation. The magnitude of the catastrophe in the atom determines the form which the released energy shall take, the minor upsets causing only long wave length radiation such as heat and visible light, while the very small number of electrons causing severe damage are responsible for the short wave length X-rays emitted. Of all the bullets shot at the target, only about 0.8 per cent bring about the desired result.

Before leaving the subject of X-ray production it should be thoroughly understood that tube-voltage and tube-current are two entirely separate factors from the practical point of view and bring about different results in the various applications of X-rays. The size of a current passing through an X-ray tube depends upon the number of free electrons available for carrying the current, and they in turn, within limits, depend upon the temperature of the filament. It must be evident that if the number of electrons striking the target is increased, then the actual quantity of X-ray emission will also be increased.

Even though the size of the tube-current affects the number of hits, it in no way influences the speed of the electrons crossing the space or the magnitude of the atomic damage wrought by any one electron. It is the impetus given to the electron by the voltage which determines the bullet's potentialities for destruction, the speed of the electron being proportional to the square root of the voltage applied to the tube. The potential energy of the electron in the cathode stream is eP (charge on the electron and Potential accelerating it) so that $eP = \frac{1}{2} mv^2$, where m is the mass of the moving electron and v its velocity. As the tube-voltage and electron speed rise, the wave length of the emitted radiation falls. But it will be seen that if these speeding electrons are made to give up their energy in varying degrees, the whole beam of radiation will not be confined to any one wave length but will cover a large range of wave lengths.

The quantity, or intensity, of the X-rays, then, is controlled by the tube-current, while the quality, or wave length, is determined solely by the tube-voltage in a given tube. Later it will be seen what an important part wave length plays in the meeting of X-rays and matter.

The Nature of X-Rays

HAVING observed that high-speed electrons on entering the atoms of the target bring about disturbances there which send X-rays speeding out through space, the next point which comes to mind concerns the nature of this discharged energy. Or, more briefly, what are X-rays?

That X-rays consist of the same ingredients as the other parts of the so-called Electromagnetic Spectrum is well known, but exactly what these constituents are is a problem which, as yet, remains unsolved. The answer to the question at present, therefore, must necessarily concern itself with a description of the radiation's behavior, effects, and characteristics rather than with any attempt to define the ultimate composition. The best line to pursue for present purposes, perhaps, is to leave the final analysis of radiation to the philosophers and give here only a brief study of some of its more important and interesting features.

X-rays are a form of energy travelling in straight lines through space with a velocity of 186,000 miles per second. In the manner and speed in which these rays travel, in their total disregard for electric and magnetic fields, and in their general behavior, all members of the Electromagnetic Spectrum family appear identical. There are, however, a few differences, the most significant of which is wave length. It has been found that these various types of energy make their way about the universe with undulating or wavelike motions. This may be compared, in some ways, to the passage of energy through water in the form of waves. In referring to the characteristics of this phenomenon it is customary to designate the distance from the crest of one wave to the crest of the next as the wave length, and to define the frequency as the number of such crests passing any point in a given time.

In the radiant energy group, it is found that each section has its own particular wave length range. Thus, the crests of radio waves travel as far apart as thousands of meters, while the gamma rays from radium have crests divided in space by only 0.01 A°

(one A° $= \frac{1}{100{,}000{,}000}$ centimeter). In between these

two extremes come the shorter radio waves, heat, visible light, ultra violet light, and X-rays, in the order of decreasing wave lengths. Since the frequency goes up as the wave length descends, the kilocycles, so familiar to the radio fan, become terrifically great in the 2 to 0.1 A° wave length range of X-rays.

Of immense scientific importance and interest is the method by which the wave character of light was demonstrated. One of the most brilliant students of optical physics, Thomas Young, arranged an experiment with a beam of light split into two parts by being passed through two pinholes. If a single ray of

light is allowed to pass through the pinholes A and B, Fig. 2, a white surface placed at X will be illuminated in alternately light and dark rings. At P, equi-distant from A and B, waves of the same phase clearly reinforce one another, but at Q the crest of one wave arrives on the trough of the other, and the two cancel out, leaving a dark area. Generally, a large number of pinholes in a row is used in the experiment to simplify the results and make the observations easier. An arrangement of this kind is known as a diffraction grating and the effects caused by the waves are called interference rings.

It was evident to the mathematicians that no such series of manufactured pinholes would be of any value in proving whether X-rays were wavelike or not. Calculations showed that if X-rays were waves, they would be infinitely smaller than those of light and would not therefore be affected greatly by any grating large enough to diffract light. Finally, it occurred to the physicist Laue, that Nature had already provided pinholes thousands of times tinier than artificial ones and that, by using these, he might show the diffraction of X-rays and their identity to light.

These natural gratings employed by Laue and his associates are the crystals which compose most solid bodies. Because of the close packing, the atoms in a crystal fall into rows, and the rows into sheets, all perfectly arranged at regular distances apart. It is this series of planes which reflect the X-rays from their faces, and cause the formation of interference rings. The practical as well as the theoretical importance of this discovery will become apparent when the structure of metals is discussed later.

This condition of interference apparently put a permanent end to the old belief that a beam of light resembled a stream of tiny rubber balls, which could be bounced off the surface of mirrors like any other group of elastic spheres. To the physicist's way of thinking there could be no system of elastic spheres imaginable which would alternately increase and decrease itself in the manner of the interference rings.

Nevertheless, even the Young experiment failed to convince a considerable number of scientists who had seen light act as only a stream of pellets could, and these closed their eyes, therefore, to the wave theory. Between the two camps there was no compromise, and only weaklings hung on the fence. Fortunately, however, some broad minded men remained, who, while being convinced of the wave character of light, saw that at times nothing short of a corpuscular explanation would fill the bill, and set out to bring these two seemingly opposite points of view together under the same roof. Largely as a result of these efforts, the present-day concepts of radiation lean strongly toward the theory that this phenomenon is both a wave and a particle effect, and as the discussion progresses instances will be observed when X-rays behave like sea waves but at other times seem to be a rain of small elastic bundles.

So far, the terms X-rays and light have been used more or less interchangeably because they are both the same type of natural phenomena and exhibit many identical characteristics. (That X-rays are really light of very short wave length depends upon other considerations too technical for the present discussion.) All radiation can be reflected, refracted and diffracted at angles, but here the variations in wave length step in, each group selecting the nature of surface necessary to bring about these effects. Whereas light can be reflected easily from ordinary polished surfaces, the wave length of X-rays is so small that no amount of surface polish causes reflection in general practice, except at very small glancing angles. The reflection and scattering of X-rays takes place from atoms or from exceedingly small faces of crystals which are the building blocks of materials. Likewise, light is readily absorbed by thin layers of matter, while X-rays slip through between the molecules and atoms of substances. It is the ability to penetrate matter which makes the X-ray such an important instrument in industrial and clinical diagnosis, but at other times it might well be said that it is the failure of the X-ray to penetrate matter that has brought to light so many valuable facts regarding the crystalline structure of materials.

Turning now from a consideration of the microscopic aspect of radiation, it is necessary to touch briefly on the behavior of a beam of radiation as a unit. Although hundreds of different atoms in the target of an X-ray tube are responsible for the emission of the total beam, for practical purposes the rays are assumed to originate from a point source. From this source the beam begins to spread out cone-wise, the distance from the target determining the area covered. At any one point the intensity of the X-rays, that is, the actual quantity of radiation present, is inversely proportional to the square of the distance from the target. This is a purely geometrical thing and may best be illustrated by the spray emitted from a garden hose. (Fig. 3).

If one cubic inch of space is selected two inches from the hose nozzle, it will be found to contain an amount of water X. If another cubic inch of space is taken 12 inches from the nozzle, however, the concentration of water will only be Y, which is 1/36 of X, according to the inverse square formula $12^2:2^2 = X:Y$. (This formula holds good only where the spreading is even in all directions). It is obvious, then, that in X-ray work the distance factor is an important one, but the fact must be understood that any distance change alters the intensity of the beam without affecting the wave length of the radiation.

In dealing with a beam of X-rays it is perhaps best to think of it as composed of two separate parts: One

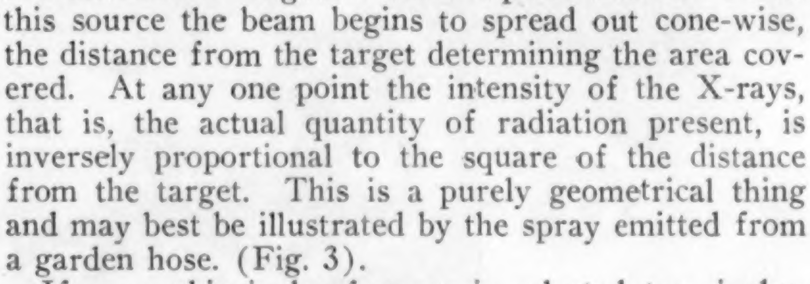


Fig. 3.

beam of radiation of a given intensity, and another beam of radiation, within the first if you like, of a definite wave length. Each of these beams has its own role to play in the work done, and either one may be changed without affecting the other. As mentioned above, the quantity of X-rays depends upon the number of filament electrons hurled against the target, while the quality of the beam is a result of the impetus given the electron by the high voltage.

In conclusion, X-rays are:

1. Produced by the impact of electrons on matter.
2. Emitted in straight lines.

3. Pass through space with a velocity of 186,000 miles per second.
4. Unaffected by electric or magnetic fields.
5. Refracted, reflected, diffracted as is light.
6. A form of radiant energy behaving sometimes as waves and sometimes as discrete particles.
7. Of a very short wave length—averaging 1 x 10^{-9} centimeters.
8. Invisible, passing from point to point in space without any transference of matter.
9. Capable of penetrating objects opaque to visible light.

X-Rays and Matter

WHEN a beam of X-rays falls upon matter, the energy of the beam is partly scattered and partly transformed, as in Fig. 4. The percentages of the

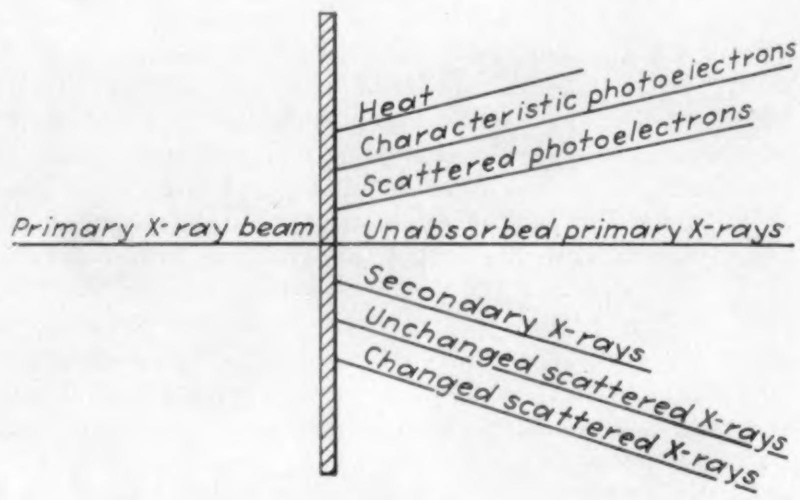


Fig. 4.

original beam which experience these various changes depend upon the wave lengths of the incident beam and the composition of the material encountered. Little need be said by way of explanation about the unabsorbed primary X-rays, since this part is merely that component of the original beam which, because of its wave length or its luck in missing deflecting matter, has traversed the material without change. As the X-rays pass through or near atoms of matter, they set up disturbances similar to that brought about in the X-ray tube target by the impact of electrons. This catastrophe within the atoms of the material robs the original X-ray of some of its energy and hands it on in the form of secondary X-rays, usually of longer wave length than the first. These secondary rays have been found to possess a wave length dependent upon the nature of the material emitting them. Thus, if a beam of X-rays impinges upon a sheet of aluminum, the secondary radiation given off will be of a wave length characteristic of the aluminum atom.

There is, however, one condition necessary for the production of characteristic secondary radiation; the wave length of the original beam must be commensurate in energy concentration with the energy of the electron within the atom struck. A definite amount of work must be done by the incoming X-ray in order to make the atom give up energy in the form of X-rays, and this work can be done only by certain wave lengths relative to given atoms. For example, if secondary X-rays are to be emitted by lead, the impinging beam must contain wave lengths associated with a production voltage of 87,000 volts. If the voltage across the X-ray tube is lower than this value, no secondaries will be emitted; but if a higher voltage is used, the secondary radiation will still be of the same wave length as though the tube were operating at 87,000 volts. In other words, no secondary X-rays will be emitted from any given element until a certain voltage has been reached, further increase in voltage being without effect.

Still another set of rays passes through the material without any change of wave-length but with a definite change in direction, this alteration being caused by scattering of X-rays from atoms and crystal faces within the matter. These rays may be scattered at any angle, depending upon the position of the atoms and crystals met with by the original beam. Nevertheless, within this group of scattered waves, X-rays of a longer wave length appear; a condition which can be accounted for only on the basis of some collision phenomena within the material.

The explanation of this condition was advanced by A. H. Compton, and as a result is known as the Compton effect. This theory states that a primary quantum or packet of X-ray energy strikes an electron in the material and imparts to the electron a certain kinetic energy resulting in a recoil. The radiation quantum is changed in its direction and proceeds with an energy reduced in proportion to the amount involved in the recoil of the electron. That the electron actually is struck has been proved by photographs of the recoil electrons made in a Wilson cloud-expansion chamber. This modified X-ray scattering is an excellent example of radiation behaving as though it were composed of discrete particles.

In addition to these different forms of radiation resulting from the meeting of X-rays and matter, there is also an ejection of electrons from the matter. These emitted electrons, sometimes called β rays, are divided into two groups: Scattered and characteristic. The scattered electrons, or photoelectrons, are those which are so loosely bound inside the atoms that the energy expended for their release is negligible. The characteristic photoelectron beam, however, is composed of electrons ejected with velocities which depend upon the particular element from which they are liberated. In some cases these velocities are high and their range in air is considerable.

By now it is evident from this description of scattering phenomena that only a part of the original beam which impinges on a material reaches the other side travelling in the same direction. To put it another way, part of an X-ray beam is absorbed in passing through matter and it is absorbed in proportion to the characteristics of the material and the wave lengths in the beam. Lead, for instance, with a density of 11.34, will absorb much more radiation per unit volume than will aluminum with a density of only 2.70. This differential absorption of X-rays by matter of varying density is the foundation on which is based the entire science of X-ray diagnosis, both clinical and industrial.

In passing through a layer of matter, X-ray intensity is reduced by a constant fraction μ per centimeter. Where ρ is the density of the material, $\frac{\mu}{\rho}$ is known as the mass-absorption coefficient. Each element has its own absorption coefficient which varies with the wave length of the incident radiation, as in the case of aluminum where the value of $\frac{\mu}{\rho}$ is 0.172 at 0.123 A° (100,000 volt X-rays) and is 0.130 at 0.064 A° (200,000 volt X-rays).

From this illustration it is apparent that most of the absorption takes place at the long wave length end of the X-ray spectrum, and that, by lengthening the waves of an X-ray beam, a point may be reached where no X-rays at all will escape absorption in a layer of given material. Penetration of matter can, therefore, be controlled to a great extent by a regulation of the wave length.

So far matter may appear to be getting all the best of the X-ray, what with reflection, scattering and absorption. Although matter undoubtedly can raise much havoc with a beam of X-rays, yet radiation itself is capable of bringing about numerous transformations of matter.

Four of the more important effects of X-rays on matter are the photographic, the ionization, the fluorescent, and the biological. The last effect is not relevant to this discussion and so may be dismissed, not however without the observation that the effect of X-rays on diseases of the human tissues is one of the most valuable scientific contributions to the welfare of mankind.

The photographic effect enables the X-ray worker to record on film facts about the internal condition of bodies which would otherwise be invisible in the whole state. Briefly, this effect depends upon the fact that wherever X-rays strike a gelatin emulsion of silver bromide, silver is reduced to a black metallic condition. It has been shown that this reduction or blackening on a photographic film, is, for all practical purposes, proportional to the intensity of the incident radiation. In taking an ordinary picture with a light-camera, the film is blackened in proportion to the intensities of light reflected from the various surfaces being photographed, but in a radiograph it is the intensities penetrating the object which register on the film. A radiograph is in reality a kind of shadowgraph, those parts easily penetrated showing black on the film, while the denser areas appear lighter. In keeping with this reversed order of things, an X-ray diagnosis is made from the negative by means of transmitted light rather than from a positive by reflected light. The photographic effect of X-rays seems to be another illustration of the corpuscular action of this type of radiation, as though little bundles of something were striking the grains of the photographic emulsion and causing a chemical change.

The use of the ionization effect as a measurement of intensity is based on the fact that X-rays passing through a gas cause it to become electrically conducting. If a beam of X-rays is directed through the air space between two charged metal plates, the air in the path of the beam will pass a current from one plate to the other in proportion to the intensity of the radiation. While this method of measuring intensity is more accurate than the photographic and is much used in research work, it is not so satisfactory for the detection of faults in industrial products since it leaves no visible record, and will not give as precise information regarding the size, shape, and nature of a defect as a film. Therefore, the film is used almost exclusively in industrial and medical diagnosis.

Another method of examining objects by X-ray is the fluoroscopic. Although not so accurate or satisfactory as the film, the fluoroscope serves well in circumstances where speed and economy are more desirable than accuracy. A screen covered with a finely powdered chemical which will fluoresce when struck by X-rays, is placed in the X-ray beam which has passed through the object being examined, and is viewed by the operator. Areas on the screen which have been struck by X-rays appear luminous, while those places in line with the rays which have been absorbed by the inspected object, remain dark. The fluoroscope is of much more practical importance in medicine than in industry, although some plants use this means of routine inspection for such things as the detection of foreign matter in tobacco, candy and like commodities.

The principle of fluorescent salts is also used to decrease the exposure time in X-ray film work. It is found that if screens of such fluorescent material are placed on either side of a film and in close contact with it, the light emitted by the screens adds greatly to the photographic effect and cuts down the amount of X-radiation necessary for a good film. In many instances, the fluorescent screen has made possible the radiographing of thicknesses of metal otherwise impractical. As a rule, however, the grain-size of the fluorescent salt coating on the screen is larger than that of the film emulsion, and the result, therefore, is a loss of distinctness and detail on the film. While the best film will be made without screens, there are times when their use is unavoidable and so may be called a necessary evil.

There are also numerous other effects of X-rays on matter but since none of them have any bearing or direct application at present on industrial work, it would seem better to omit them and turn to some practical examples of X-ray uses.

X-Rays in Industry

THE application of X-rays in industry for the determination of flaws and internal defects in metal parts, is a more recent development than that of medical diagnosis by X-ray. Despite this fact, X-ray studies of industrial materials have progressed so rapidly in the last few years that the value of this method of inspection no longer may be questioned or passed up as a fad. X-ray examination of welds, castings, radio

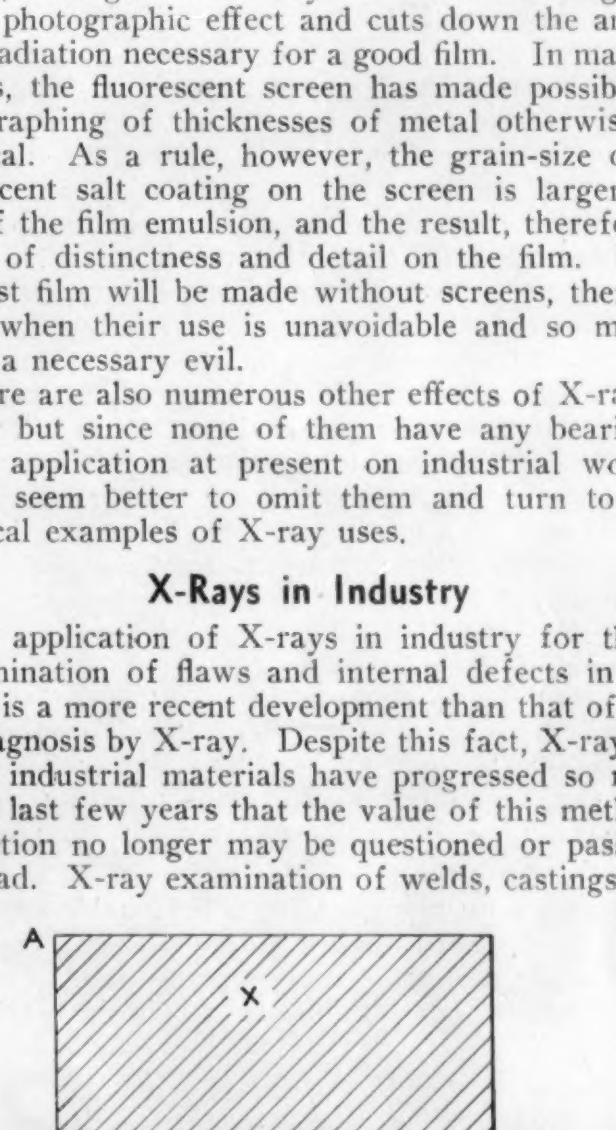


Fig. 5.

tubes, and countless other manufactured articles is now a routine occurrence in numerous plants throughout the world, and has been so thoroughly covered in the literature that no review of this work is necessary. Therefore, only a very brief outline will be given here, covering a few of the interesting points encountered in the application of X-rays in industry.

As mentioned previously, the basis of all radiography, medical and industrial, is the differential absorption of X-rays by matter of varying densities. Thus, in radiographing an object containing areas which, intentionally or not, differ in density from the surrounding material, those areas will register on the

film, providing of course they are not too small. If, for example, in a sample of carbon steel, the carbon has precipitated in one section, that area will be of a lower density than the neighboring iron and will allow X-rays to pass more freely. The result will be a black spot on the film of increased exposure. On the other hand, any section of increased density will absorb the X-rays and record a lighter unexposed section on the film. If handled correctly, areas of increased and decreased density may be recorded on the film in faithful reproduction of the original as to size and shape. There are times, however, when this is very difficult to do, especially if the defect can not be brought close to film. Fig. 5 represents a piece of metal showing an internal defect at X.

Here the image of the flaw may become somewhat blurred in traveling from X to the film, due to the diffuse scattering of the beam traversing the material. If the object were turned so that surface A was next to the film, the distortion would not occur, because the distance from X to the film would not be great enough to allow the scattering much spread.

As a general rule, defects about 1½ to 2 per cent of the total thickness of the object X-rayed can be detected, and in some cases flaws as small as 1 per cent are demonstrated. In speaking of the total thickness of an object, it must be kept in mind that this refers to the total amount of material present, not to the outside measurements. For example, the apparent thickness of a casting may be 1 ft., but, because of the internal construction, the total metal thickness may be only 4 in. This is an important point in considering the advisability of X-ray inspection.

In some of the past sections the factors of voltage, current and the resulting quality and quantity of X-rays have been stressed. It was shown that voltage was responsible for the wave length of an X-ray beam, and current for the intensity, and it was brought out that the wave length more or less controlled the penetration of the rays. If a film of a casting shows no picture after a reasonable exposure to X-rays, it means that the amount of X-rays absorbed in the casting is much greater than it should be. The way to correct this, as a rule, is not by increasing the intensity of the beam but by decreasing the wave length; that is, raising the voltage. A good illustration of this problem might be the shooting of rifle bullets at a piece of wood. If one 0.22 with a certain amount of energy will not pierce the wood, simply increasing the number of bullets fired will do nothing to remedy the situation. In order to penetrate the wood, the energy of the bullets, not the quantity, must be raised.

However, if the voltage across the X-ray tube is raised too much, a point is reached where the rays penetrate the defect and surrounding material so completely that it is almost impossible to differentiate one from the other. Therefore, the ideal film is the one on which the rays have just penetrated the defect but not the material, if the defect is of low density, or have just penetrated the material but not the defect where the flaw is denser than the rest of the object.

One of the outstanding contributions to modern science in the field of industry is the application of X-rays to the study of the atomic and crystalline structure of metals. When an X-ray beam passes through a specimen of matter, some of the rays are reflected from the faces of the crystals and will form a pattern on a film suitably placed, corresponding to the internal design of the matter. This diffraction work has been of inestimable value in discovering the different changes taking place within materials subjected to various treatments. The whole subject of diffraction is very interesting but also very complex, and so no attempt will be made here to go into the matter. Those who are anxious to study this phase of X-ray work will find the subject thoroughly covered in some of the books on the subject.

There are many other interesting problems and possibilities in industrial X-ray work well worth discussion, but as was mentioned at the outset, the purpose of this article is to give the busy engineer a few of the basic facts and theories pertaining to the subject. It is hoped that what few points are presented here will enable the reader to study the ever-increasing number of articles on X-rays appearing in the various journals with a slightly better understanding of the meaning and the work behind them.

(Editorial Comment continued from page 34)

which failures still persist without clear explanation.

We are still a bit puzzled as to just when we need impact toughness. The cast Ford crankshaft would not be classed, by any sort of notched-bar impact test, as suitable for severe duty, yet we haven't the slightest fear that the one in our V8 will fail. The performance of a couple of million crankshafts in service is too convincing. The answer must be that it isn't the type of service in which impact resistance is needed. On the other hand, not so many years ago most designers insisted on high toughness and impact resistance in automobile crankshafts. How, then, do we know that designers are right in demanding impact resistance in lots of other places where they still call for it, and whether high test cast iron, quick anneal malleable and the like, which have some kinds of toughness but not very high notched bar impact resistance, might not be usable where tough forgings or ductile non-ferrous alloys are demanded today?

What has damping capacity, which the cast crankshaft and that general class of materials do possess, to do with it? May not the ability to dissipate energy without deformation sometimes be substituted for the ability to dissipate it in very local deformation? Obviously there is some limit to such a substitution, but where is the limit? What degree of ductility, notch-toughness, local plasticity or damping does a given part need and how is the engineer going to know and how pass on his requirements to the metallurgist if he does know?

Maybe something of the order of 10 ft. lbs. impact, provided that value is retained in test pieces of various sizes and notches, or under various speeds of impact, and at the lowered temperatures that might be encountered, would do just as well as 40.

If we could know this, we might be able to build the actually required impact resistance into cheap and cheaply made alloys, while we are deterred from trying to do anything in that line as long as the engineer demands 40.

Hence we commend Dr. Hoyt's thoughtful discussion of the subject of notched bar testing not only to the metallurgist, but especially to the engineer, who may thereby be emboldened, after exploration of their properties along the lines he suggests, experimentally to try out types of alloys in services from which he now excludes them without trial. There may be more cases like the Ford crankshaft lying around, if we look for them.—H. W. G.

Phosphorus as an Alloying Element in Low Carbon, Low Alloy Steels—II

An Experimental Study

By C. H. LORIG and D. E. KRAUSE

Metallurgists, Battelle Memorial Institute, Columbus, Ohio

THE first part of this study, published in the January issue, dealt with such subjects as "The Effect of Phosphorus on the Gamma Loop," "Effect of Carbon plus Manganese," "Static and Impact Properties of Low Carbon, Phosphorus Steels' and "The Effect of Carbon and Aluminum upon Impact."

Effect of Alloying Elements Upon Impact

IT IS NECESSARY to determine what effect other alloying elements may have upon impact resistance Copper is a promising alloying element for this purpose, since Lorig and Smith[3] showed that intergranular embrittlement in malleable cast iron, evidenced by loss in impact resistance after heating to the temperature of the galvanizing bath, and presumed to be due to the presence of silicon and phosphorous, is markedly reduced by copper. In malleable iron with 0.21 per cent P, the addition of about 2 per cent Cu practically eliminates the embrittlement.

On account of the good behavior in atmospheric corrosion of steels high in P and containing Cu, Cu is a promising alloying element for use in P steels, on another score.

Using low carbon alloys of similar base composition to those of Table 1 and without Al addition, the effects of Cu and Ni were studied. Though a wider range of phosphorus compositions as well as other heat treatments were studied, it will suffice to record in Table 3 the impact data for only a few P compositions and for material as forged and after annealing at 1325 deg. F.

Table 3.—Impact Data for a Few P Compositions

P (Per Cent)	Cu (Per Cent)	As Forged, Charpy ft.-lbs.	Annealed, Charpy ft.-lbs.
0.26	0.31	35	14½
0.43	0.31	1½	2
0.31	1.04	25½	7
0.47	1.04	1½	2
0.31	1.65	4½	7
	Ni		
0.29	0.50	28½	3½
0.45	0.54	1½	7

The as-rolled alloys of the lower P content are certainly not embrittled by these additions, but the additions do not suffice to make the 0.45 per cent P alloy tough.

A series of aluminum-treated phosphorus bearing steels was prepared with a carbon content of about 0.06 to 0.10 per cent, whose compositions are shown in Table 4 and whose tensile, hardness and impact properties, determined on ½-in. thick plate, are given in Table 5. Fig. 14 shows the various types of impact fractures obtained.

From the data so far available one would not have expected that any of the 0.60 per cent P steels nor the one 0.45 per cent P steel would show appreciable resistance to impact. Yet the Cu-Mo and Cu-Cr combinations with 0.60 per cent P and the Cu-Ti combination with 0.45 per cent P all showed in one or both of the as-rolled or the 1250 deg. F. annealed conditions, over 10 ft. lbs.

Table 4.—Chemical Composition of Al-Treated Ingots*

Ingot	C	Mn	Si	P	Cu	Other alloys
	Per Cent					
43	0.07	0.41	0.04	0.03	..	...
45	0.06	0.45	0.04	0.27	..	...
46	0.06	0.45	0.04	0.60	..	...
47	0.06	0.45	0.04	0.03	1.5	...
48	0.07	0.47	0.02	0.26	1.4	...
49	0.06	0.45	0.04	0.60	1.5	...
50	0.06	0.45	0.04	0.03	1.5	0.35 Mo
51	0.10	0.52	0.05	0.25	1.5	0.26 Mo
52	0.06	0.45	0.04	0.60	1.5	0.35 Mo
53	0.06	0.45	0.04	0.03	1.5	0.70 Mo
54	0.08	0.58	0.05	0.26	1.4	0.60 Mo
55	0.06	0.45	0.04	0.60	1.5	0.70 Mo
56	0.06	0.45	0.04	0.02	1.5	0.60 Cr
57	0.07	0.41	0.06	0.27	1.5	0.54 Cr
58	0.06	0.45	0.04	0.60	1.5	0.60 Cr
59	0.06	0.45	0.30	0.03	1.5	0.20 Zr
60	0.06	0.49	0.24	0.28	1.4	0.20 Zr
61	0.06	0.45	0.30	0.60	1.5	0.20 Zr
62	0.06	0.45	0.04	0.03	1.5	0.15 V
63	0.06	0.38	0.02	0.25	1.5	0.19 V
64	0.06	0.45	0.04	0.60	1.5	0.15 V
65	0.06	0.48	0.06	0.45	1.1	0.15 Ti

* Sulphur was found to be 0.032 per cent.

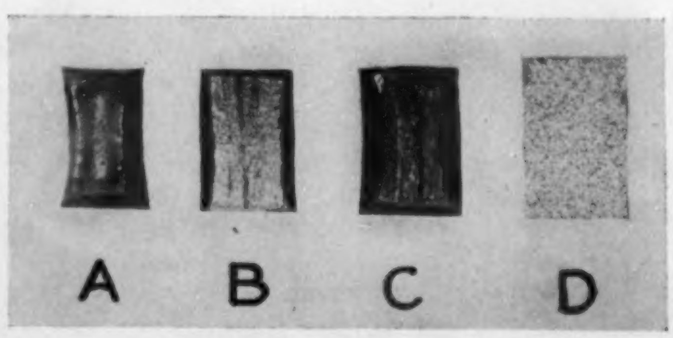


Fig. 14. Types of Impact Fractures in Steels of Table 5.

The Cu-Mo and Cu-Cr alloys were therefore given a variety of heat treatments, which, with the impact results, are given in Table 6.

Further impact tests were made on these Cu-Mo-P and Cu-Cr-P alloys at 212 deg. F., room temperature and 0 deg. F. The results are in Table 7. None of

Table 5.—Mechanical Properties of Alloyed Phosphorus Steels.

Specimen	Heat treatment [a]	Composition: P (Per cent)	Composition: Cu (Per cent)	Composition: Other alloys (Per cent)	Tensile Properties: Ultimate strength, p.s.i.	Tensile Properties: Yield strength, p.s.i.	Tensile Properties: Elong., 2 in., per cent	Tensile Properties: Red. of area, per cent	Brinell	Charpy impact, ft.-lbs.	Type of fracture
43	1	0.03			49,600	36,900	47	77	103	59	A
	2	"			50,300	36,500	47	77	99	58	A
	3	"			45,400	30,000	49	78	92	53	A
	4	"			48,300	35,200	46	79	99	57	A
45	1	0.27			70,100	49,300	36	63	149	32	A
	2	"			70,400	47,700	38	64	143	28	A
	3	"			64,300	42,700	37	62	137	6	A
	4	"			65,700	45,000	36	69	140	31	B
46	1	0.60			75,800	57,800	15	13.5	179	1.5	D
	2	"			74,900	51,500	35	61	174	1.0	C
	3	"			63,600	49,000	7	6	159	1.0	D
	4	"			74,400	50,000	40	66	170	1.1	C
47	1	0.03	1.5		67,300	56,700	37	73	143	50	A
	2	"	"		68,300	57,100	39	70	143	52	A
	3	"	"		62,700	52,300	38	70	131	47	A
	4	"	"		62,500	54,000	40	77	137	56	A
48	1	0.26	1.4		80,800	65,800	27	63	179	31	B
	2	"	"		80,200	63,400	35	65	167	28	B
	3	"	"		74,300	55,800	34	65	156	25	A
	4	"	"		71,300	56,300	38	73	152	42	B
49	1	0.60	1.5		97,000	83,600	30	56	229	10	C
	2	"	"		92,500	73,400	29	52	207	1.8	C
	3	"	"		83,900	65,100	32	55	192	3	C
	4	"	"		88,600	75,200	33	61	201	3	C
50	1	0.03	1.5	0.35 Mo	82,400	71,300	32	66	179	45	A
	2	"	"	"	77,800	58,500	36	72	156	53	A
	3	"	"	"	64,800	52,700	38	68	131	37	A
	4	"	"	"	71,800	64,500	35	75	156	52	A
51	1	0.25	1.5	0.26 Mo	99,200	79,400	28	55	212	28	B
	2	"	"	"	93,900	62,500	30	57	192	21	A
	3	"	"	"	81,100	60,400	32	58	170	22	A
	4	"	"	"	84,600	73,900	30	46	183	30	B
52	1	0.60	1.5	0.35 Mo	108,000	89,100	30	56	229	11	C
	2	"	"	"	107,900	73,700	28	48	217	2	B
	3	"	"	"	91,200	70,000	27	52	207	1.5	C
	4	"	"	"	94,800	78,800	30	58	217	14	C
53	1	0.03	1.5	0.70 Mo	87,800	71,800	29	67	192	45	A
	2	"	"	"	79,700	53,700	35	70	159	52	A
	3	"	"	"	71,100	56,100	35	65	146	37	A
	4	"	"	"	76,100	68,000	33	75	163	53	A
54	1	0.25	1.4	0.60 Mo	113,000	84,200	25	47	223	25	A
	2	"	"	"	101,000	66,000	29	51	207	18	A
	3	"	"	"	82,300	60,700	32	62	167	27	A
	4	"	"	"	89,800	76,300	31	67	192	37	C
55	1	0.60	1.5	0.70 Mo	105,000	75,000	28	50	223	1.2	B
	2	"	"	"	107,500	72,900	27	47	217	1.5	C
	3	"	"	"	92,700	70,000	32	56	201	1.5	C
	4	"	"	"	101,400	83,300	28	55	223	22	C
56	1	0.02	1.5	0.60 Cr	75,000	61,600	33	72	163	51	A
	2	"	"	"	66,400	55,000	40	77	140	59	A
	3	"	"	"	64,900	53,700	39	74	137	56	A
	4	"	"	"	66,600	56,000	36	79	143	59	A
57	1	0.27	1.5	0.54 Cr	86,300	74,900	30	63	187	32	B
	2	"	"	"	78,700	62,600	34	67	170	28	B
	3	"	"	"	75,000	56,400	35	64	159	35	B
	4	"	"	"	74,400	57,500	36	71	159	45	C
58	1	0.60	1.5	0.60 Cr	100,000	85,500	29	58	223	11	C
	2	"	"	"	94,100	73,400	29	57	212	1.3	C
	3	"	"	"	87,400	66,800	35	57	192	7	C
	4	"	"	"	92,800	78,600	30	59	201	11	C
59	1	0.03	1.5	0.20 Zr + 0.30 Si	71,200	63,500	32	69	156	41	A
	2	"	"	"	65,900	49,800	33	72	137	48	A
	3	"	"	"	66,900	52,300	33	57	146	28	A
	4	"	"	"	65,000	58,000	35	75	140	46	A
60	1	0.28	1.4	0.20 Zr + 0.24 Si	88,600	76,800	30	60	197	31	B
	2	"	"	"	81,300	64,800	34	64	183	32	B
	3	"	"	"	77,900	61,700	30	59	170	9	A
	4	"	"	"	78,700	67,200	33	69	174	42	B
61	1	0.60	1.5	0.20 Zr + 0.30 Si	101,000	87,600	30	55	229	6.5	C
	2	"	"	"	96,700	75,700	29	52	217	1	C
	3	"	"	"	89,600	71,500	29	55	207	1.2	C
	4	"	"	"	90,200	77,300	32	58	207	2	C
62	1	0.03	1.5	0.15 V	85,100	77,000	28	64	187	40	A
	2	"	"	"	73,900	60,500	35	69	159	39	A
	3	"	"	"	70,400	56,900	32	69	149	33	A
	4	"	"	"	77,500	68,600	26	75	174	53	A
62	1	0.25	1.5	0.19 V	93,000	83,500	29	62	207	34	B
	2	"	"	"	79,100	63,300	35	67	170	31	B
	3	"	"	"	78,000	62,300	32	67	174	30	B
	4	"	"	"	78,800	64,600	33	74	167	44	C
64	1	0.64	1.5	0.15 V	97,400	85,800	31	59	241	1.5	C
	2	"	"	"	91,400	72,200	27	59	207	1.2	C
	3	"	"	"	87,700	70,000	33	60	197	1.5	C
	4	"	"	"	92,100	78,300	32	63	217	4.5	C
65	1	0.45	1.1	0.15 Ti	90,200	78,300	31	59	207	24	C
	2	"	"	"	85,100	68,500	33	60	187	1.5	C
	3	"	"	"	80,500	65,200	32	59	187	2.5	C
	4	"	"	"	80,800	68,500	33	66	183	30	C

[a] 1. No heat treatment—as rolled.
2. ½ hr. at 1725 deg. F.—air cooled.
3. ½ hr. at 1725 deg. F.—furnace cooled.
4. 4 hrs. at 1250 deg. F., followed by air cooling.

Table 6.—Effect of Heat Treatment Upon the Charpy Impact Values of Some Phosphorus Steels.

Specimen	P Per cent	Cu Per cent	Other alloys	Heat Treatment 5	6	7	8	9	10	11	12
52	0.60	1.5	0.35 Mo	26	1.5	22	7.5	2.5	1.2	17	25
54	0.26	1.4	0.6 Mo	31	43	43	37				
55	0.60	1.5	0.7 Mo	12	12	19	6				
57	0.27	1.5	0.54 Cr	50	39	47	46				
58	0.60	1.5	0.60 Cr	23	1.0	23	1.5	2	1.2	1.0	2.0

5. 4 hrs. at 1275 deg. F., air cool.
6. 1 hour at 1850 deg. F., air cool; 4 hrs. at 1275 deg. F., air cool.
7. 4 hrs. at 1275 deg. F., furnace cool.
8. 4 hrs. at 1275 deg. F., water quench.
9. 1 hour at 1850 deg. F., water quench.
10. 1 hour at 1850 deg. F., water quench; 1 hr. at 700 deg. F., water quench.
11. 1 hour at 1850 deg. F., water quench; 1 hr. at 1000 deg. F., water quench.
12. 1 hour at 1850 deg. F., water quench; 4 hrs. at 1275 deg. F., water quench.

the 0.60 per cent P alloys remained tough at 0 deg. F., but it is evident that with suitable heat treatment, the aluminum-treated Cu-Mo and Cu-Cr steels with 0.25 per cent P can be kept tough at 0 deg. F.

The behavior of these combinations made it appear worth while to study the separate effect of individual alloying elements in more detail.

Table 7.—Effect of Temperature upon Charpy Impact Values of Phosphorus Steels.

Specimen	treatment [a]	P Per cent	Cu Per cent	Other alloys	Testing temp., deg. F. 0	85	212
52	5	0.60	1.5	0.35 Mo	3.5	26	21
	6	"	"	"	1.0	1.5	23
54	5	0.25	1.4	0.6 Mo	33	31	36
	6	"	"	"	34	43	49
55	5	0.60	1.5	0.7 Mo	2	12	28
	6	"	"	"	1	12	41
57	5	0.27	1.5	0.54 Cr	38	50	40
	6	"	"	"	2.5	39	50
58	5	0.60	1.5	0.60 Cr	2.5	23	29
	6	"	"	"	2.0	1.0	22

[a] See Table 2.

Impact Properties of Phosphorus Steels

To explore the region of decreased impact resistance in iron-phosphorus alloys, a systematic study of the impact properties of alloys falling just outside and just within the brittle range of composition was made. The study was divided into two parts: First, an investigation of the critical amount of phosphorus which induces room temperature brittleness in the C-P-Fe alloys; and second, an investigation of the influence of nine alloying elements on the impact resistance of C-P-Fe alloys which are normally "border-line" alloys.

The steels were prepared as 15-lb. high frequency furnace melts which were subsequently split three ways to give three 5-lb. ingots differing from one another in the amount of one constituent only. All heats were treated with 0.10 per cent aluminum to effect grain refinement. The 5-lb. ingots were subsequently forged and rolled to ¾-in. rounds. Before being put through the last pass in the mill, the steels were reheated to a temperature at least 50 deg. F. above the lower critical temperature in order that the steels be finished above the critical. Keyhole-notched Charpy impact specimens were machined from the hot-rolled rods and were tested at room temperature without further heat treatment. The results of tests on the C-P-Fe alloy series are tabulated in Table 8.

Room temperature brittleness occurred in the 0.12 to 0.16 per cent carbon alloys when the phosphorus was between 0.33 and 0.36 per cent. In the higher carbon alloys, those with 0.24 to 0.26 per cent carbon, brittleness occurred in one specimen with 0.29 per cent P (Steel No. 9) to indicate clearly that the limiting phosphorus content for ductility is lowered by carbon.

The following elements were alloyed to C-P-Fe alloys; silicon, copper, molybdenum, nickel, chromium, manganese, vanadium, titanium and zirconium. Impact data on, and intended compositions of, these alloys are given in Table 9. All heats to which silicon or manganese were not alloyed contained about 0.05 per cent Si and 0.30 per cent Mn.

In the case of silicon, which was expected to embrittle the alloys, the P content was lowered to 0.35 per cent in the 0.10 per cent C and to 0.25 per cent in the 0.20 per cent C to bring the alloy just on the border line. The results indicate that the border-line alloys will tolerate up to 0.5 per cent Si or more without being injured, but that the tendency of Si is toward embrittlement. As heat 1187 shows, the presence of 1.50 per cent Si shoves the brittle range back to 0.20 per cent P. With all the other elements used, the C-P compositions just over the border line were employed. The results indicate that 0.75 per cent copper is a definite help, but increase in copper decreases the benefit, 1.5 per cent being only a slight help and 2.5 per cent showing erratic results in the low C and no help at all in the high C. One would say that 1 per cent Cu could be tolerated without increasing the embrittling tendency. It is to be expected that, in these border-line alloys, the addition of a hardening element, even

Table 8.—Impact Properties of Hot-Rolled, Carbon-Phosphorus-Iron Alloy.

Heat No.	Steel No.	Approx. Roll Finishing Temp., deg. F.	Composition C	P	Mn	Si	S	Charpy Impact, Ft.-Lbs. Specimen No. 1	Specimen No. 2	Average Value
			Per cent							
1174	13	1900	0.12	0.28	0.36	0.08	0.04	21.0	20.5	20.5
1174	14	1950		0.32				17.0	19.5	18.0
1174	15	2000		0.36				4.0	4.0	4.0
1171	4	1700	0.16	0.23	0.36	0.11	0.04	27.0	26.0	26.5
1171	5	1750		0.27				20.5	22.5	21.5
1171	6	1800		0.33				16.5	17.5	17.0
1172	7	1650	0.24	0.23	0.36	0.09	0.04	18.0	18.0	18.0
1172	8	1700		0.25				14.0	15.0	14.5
1172	9	1750		0.29				1.0	15.0	8.0
1173	10	1650	0.26	0.15	0.35	0.09	0.039	22.0	23.0	22.5
1173	11	1650		0.20				21.0	19.5	20.0
1173	12	1700		0.19				19.5	19.0	19.0

though it is helpful in small amounts, will reach a point at which a still higher addition is no help or even somewhat harmful because of the added hardening. This is the case with Mo which has a definitely beneficial tendency at 0.25 per cent, and even at 1 per cent has not dropped the impact quite to the 1.5 ft. lb. value that would be shown in its absence. Tolerance of any normal amount of Mo likely to be used is thus indicated.

Outside of one low value all the data on Ni indicate not only tolerance of it up to at least 2 per cent but also a definite improvement due to its presence.

Chromium is even more outstanding. While 0.35 per cent Cr did not greatly improve the 0.10 per cent C, 0.40 per cent P alloy, higher amounts did, and even 0.35 per cent helped the 0.20 per cent C, 0.35 per cent P alloy. Marked improvement with a Cr content of about 1 per cent is indicated.

Manganese classes as helpful, and a tolerance of something around 1 to 1.25 per cent Mn is indicated.

Vanadium was slightly helpful in small amount in the 0.20 per cent C, 0.35 per cent P alloy. Titanium and zirconium also showed up better in this than in the lower C, higher P alloy.

One would conclude then, that, unless balanced by some helpful element, Si should be held to 0.5 per cent, that 1 per cent Cu or 1 per cent Mn would be at least neutral, probably beneficial, Ni in reasonable amounts will be beneficial, Cr at around 1 per cent markedly beneficial, small amounts of Ti or Zr admissable and possibly beneficial, while only a very little V would appear to be helpful. In non Al-treated steels, the effect of V, Ti or Zr might be more marked.

From the point of view of cheap, low alloy steels it would appear that, within limits as to amounts used, the elements Cr, Ni, Cu, Mo, Mn can be used in con-

Table 9.—Impact Properties of Hot-Rolled Alloyed C-P-Fe Alloys.

Heat No.	Steel No.	Approx. Roll Finishing Temp., deg. F.	Composition C	Composition P	Composition Alloy	Charpy Impact, Ft.-Lbs. Specimen No. 1	Charpy Impact, Ft.-Lbs. Specimen No. 2	Charpy Impact, Ft.-Lbs. Average Value
			Per Cent					
1192	16	1850	0.10	0.35	0.25 Si	20.5	22.5	21.5
1192	17	1950	0.10	0.35	0.50 Si	32.5	29.0	30.5
1192	18	1950	0.10	0.35	1.00 Si	1.5	1.5	1.5
1193	19	1850	0.20	0.25	0.25 Si	18.0	17.5	17.5
1193	20	1850	0.20	0.25	0.50 Si	5.0	20.0	12.5
1193	21	1850	0.20	0.25	1.00 Si	15.0	15.5	15.0
1187	A	1850	0.04	0.01	1.50 Si	36.5	33.5	35.0
1187	B	1950	0.04	0.20	1.50 Si	1.5	1.5	1.5
1187	C	1950	0.04	0.30	1.50 Si	1.5	1.5	1.5
1194	22	1900	0.10	0.40	0.75 Cu	11.0	7.5	9.0
1194	23	1900	0.10	0.40	1.50 Cu	4.0	3.0	3.5
1194	24	1900	0.10	0.40	2.50 Cu	1.0	26.5	13.5
1195	25	1850	0.20	0.35	0.75 Cu	16.5	18.0	17.0
1195	26	1850	0.20	0.35	1.50 Cu	7.0	7.0	7.0
1195	27	1850	0.20	0.35	2.50 Cu	1.5	1.5	1.5
1196	28	1900	0.10	0.40	0.25 Mo	20.5	3.5	11.5
1196	29	1900	0.10	0.40	0.50 Mo	3.5	7.0	5.0
1196	30	1900	0.10	0.40	1.00 Mo	2.5	2.5	2.5
1197	31	1850	0.20	0.35	0.25 Mo	15.0	12.0	13.5
1197	32	1850	0.20	0.35	0.50 Mo	7.0	12.0	9.5
1197	33	1850	0.20	0.35	1.00 Mo	3.5	3.5	3.5
1198	34	1900	0.10	0.40	0.50 Ni	18.5	15.5	17.0
1198	35	1900	0.10	0.40	1.00 Ni	1.5	17.0	9.0
1198	36	1900	0.10	0.40	2.00 Ni	12.5	15.0	13.5
1199	37	1850	0.20	0.35	0.50 Ni	13.5	13.0	13.0
1199	38	1850	0.20	0.35	1.00 Ni	12.0	12.5	12.0
1199	39	1850	0.20	0.35	2.00 Ni	7.5	5.5	6.5
1200	40	1900	0.10	0.40	0.35 Cr	2.5	2.5	2.5
1200	41	1900	0.10	0.40	0.75 Cr	18.0	21.0	19.5
1200	42	1900	0.10	0.40	1.50 Cr	19.0	23.0	21.0
1201	43	1850	0.20	0.35	0.35 Cr	13.0	14.5	13.5
1201	44	1850	0.20	0.35	0.75 Cr	12.0	17.0	14.5
1201	45	1850	0.20	0.35	1.50 Cr	9.5	12.5	11.0
1202	46	1900	0.10	0.40	0.75 Mn	10.5	6.0	8.0
1202	47	1900	0.10	0.40	1.25 Mn	13.0	1.0	7.0
1202	48	1900	0.10	0.40	1.75 Mn	1.0	2.0	1.5
1203	49	1850	0.20	0.35	0.75 Mn	12.5	13.0	12.5
1203	50	1850	0.20	0.35	1.25 Mn	14.0	15.5	14.5
1203	51	1850	0.20	0.35	1.75 Mn	1.0	1.0	1.0
1204	52	1900	0.10	0.40	0.12 V	1.5	5.5	3.5
1204	53	1900	0.10	0.40	0.22 V	2.0	2.5	2.0
1204	54	1900	0.10	0.40	0.37 V	1.0	2.5	1.5
1205	55	1850	0.20	0.35	0.12 V	15.0	14.0	14.5
1205	56	1850	0.20	0.35	0.22 V	8.0	9.0	8.5
1205	57	1850	0.20	0.35	0.37 V	2.0	2.5	2.0
1206	58	1900	0.10	0.40	0.15 Ti	2.0	7.0	4.5
1206	59	1900	0.10	0.40	0.25 Ti	5.0	2.0	3.5
1206	60	1900	0.10	0.40	0.40 Ti	3.0	1.5	2.0
1207	61	1850	0.20	0.35	0.15 Ti	15.0	15.0	15.0
1207	62	1850	0.20	0.35	0.25 Ti	15.0	15.0	15.0
1207	63	1850	0.20	0.35	0.40 Ti	2.5	13.5	8.0
1208	64	1900	0.10	0.40	0.15 Zr	17.5	10.5	14.0
1208	65	1900	0.10	0.40	0.25 Zr	1.0	1.0	1.0
1208	66	1900	0.10	0.40	0.40 Zr	1.0	2.0	1.5
1209	67	1850	0.20	0.35	0.15 Zr	11.0	12.5	11.5
1209	68	1850	0.20	0.35	0.25 Zr	1.0	10.0	5.5
1209	69	1850	0.20	0.35	0.40 Zr	14.5	12.5	13.5

junction with P, while Si would need to be limited. In a complex steel carrying several of these elements, the effects may or may not be additive and one would expect that too great hardness due to the cumulative effect of the different elements would at some point introduce brittleness. However, it would seem that in most of the low alloy combinations being used for high-yield strength steels, the addition of P might well be considered, for enhancement both of yield strength and corrosion resistance. At any rate, it seems quite unnecessary to hold the P in such steels down to the limits usually imposed for structural steel unless the use is such that severe cold-working is to be imposed. The work hardening properties of the various P containing alloys would have to be determined before the proper limits could be set.

Without doubt, the impact resistance of some of these compositions, particularly those with Mo, could be improved by heat treatment.

All the steels were finished on hot-rolling at 1850 deg. F. or above, and cooled in air. This treatment may have induced brittleness in some steels, especially those having air-hardening qualities, so that the above data are not strictly a criteria of the effect of each element under different conditions. A prolonged draw treatment at 1250 deg. F., would certainly have improved the molybdenum steels and might have improved the copper, the manganese, the vanadium and the titanium steels.

The data of Tables 5 and 6 indicate that the impact behavior of a phosphorus steel with two or three other alloying elements may be different, in some cases markedly better, than would be expected from the behavior of the individual alloying elements, so too sweeping predictions should not be made prior to trial. However, the helpful, neutral, or harmful effect of an individual alloying element should be indicated by Table 9.

Static Properties of Phosphorus Steels

So much for impact. We may now turn to a further consideration of the static properties.

Table 5 shows that, in every case, whatever the other

Table 10.—Mechanical Properties of 22 Gage Sheet.

Heat No.	P, Per Cent	Other * Elements, Per Cent	Heat Treatment	Tensile Strength, p.s.i.	Yield Strength, p.s.i.	Elongation in 2 in., %	Rockwell "B" Hardness	Charpy Impact,** Ft.-Lbs. C	D	E	Olsen Ductility, In.	Repeated Bend Tests, No. of Bends
571	0.06	0.50 Ni	A	43,500	34,000	32		36	45	42		
			B	43,500	30,000	33	48				0.336	67
575	0.19	0.50 Ni	A	59,000	52,000	27		37	41	23		
			B	58,500	51,000	24.5	72				0.270	60
577	0.29	0.50 Ni	A	65,500	57,300	28		28.5	7.5	3.5		
			B	60,500	45,000	28	73				0.305	60
605	0.45	0.54 Ni	A	73,000	61,000	21		1.5	2.5	7.0		
			B	73,000	57,000	24.5	81				0.274	21
605	0.72	0.54 Ni	A	80,000	68,500	17		1.0	1.0	1.0		
			B	86,500	75,000	20.5	91				0.210	17
605	1.00	0.54 Ni	A	92,000	89,000	14		0.5	1.0	1.0		
			B	92,000	77,000	15	91				0.162	9
606	0.05	0.31 Cu	A	50,000	42,500	19		42.5	47.5	47.5		
			B	51,500	42,000	24.5	62				0.268	68
606	0.26	0.31 Cu	A	59.500	49,500	23		35.0	30.5	14.5		
			B	59,500	45,500	28.5	68				0.290	37
606	0.43	0.31 Cu	A	68,500	58,000	19		1.5	2.0	2.0		
			B	72,000	60,500	21.5	81				0.252	40
607	0.70	0.31 Cu	A	90,000	67,000	21		1.0	1.5	1.5		
			B	84,000	67,500	23	87				0.170	2
607	0.94	0.31 Cu	A	71,000	71,000	...		0.5	0.5	0.5		
			B	91,500	73,500	16.5	90				0.121	1½
608	0.11	1.04 Cu	A	55,000	48,000	19		40.5	43.5	40.5		
			B	53,500	45,500	19.5	69				0.258	62
608	0.31	1.04 Cu	A	65,500	58,500	19		25.5	18.5	7.0		
			B	66,000	58,000	16.5	79				0.240	36
608	0.47	1.04 Cu	A	78,000	71,500	18		1.5	2.0	2.0		
			B	79,500	73,000	20.5	86				0.238	31
609	0.71	1.04 Cu	A	94,500	81,500	19		0.5	1.0	1.0		
			B	91,000	78,500	21.5	92				0.241	19
609	0.96	1.04 Cu	B	96,000	80,000	18.5	94	0.5	0.5	1.0	0.155	3
609	0.96	1.04 Cu; 0.53 Cr	B	91,000	73,500	20.0	92	0.5	0.5	1.0	0.116	3
610	0.15	0.83 Cu	A	51,500	39,000	22.0		48.0	37.0	45		
			B	51,000	37,500	24.5	63				0.274	39
610	0.31	1.66 Cu	A	80,000	71,000	14.0		4.5	2.0	7.0		
			B	69,000	61,000	17.5	81				0.254	38
610	0.60	3.2 Cu	A	88,500	84,500	10		1.5	1.5	2.5		
			B	83,000	74,000	17.5	89				0.201	28
610	0.88	4.7 Cu	A	104,000	100,000	16		1.0	1.0	1.0		
			B	90,000	75,500	15.5	91				0.185	27

* Alloys not aluminum treated; carbon content about 0.02%; manganese, 0.07%; silicon, 0.03%; and sulphur, 0.02%.
** Charpy impact specimens cut from ½-inch forged plate.
C—Specimen tested in as-forged condition. D—Specimen tested after heating to 1625 deg. F. for ¾ hr. and air-cooled. E—Specimen tested after holding for 10 hrs. at 1325 deg. F. followed by furnace cooling to 900 deg. F., then air-cooled.
Heat Treatment:
A—Rolled, heated to 1725 deg. F. for ½ hr., then air cooled.
B—Rolled, box annealed at 1325 deg. F. for 8 hrs., furnace cooled to 1000 deg. F., then air cooled.

alloys added, or whatever the heat treatment used, these steels of 0.06 to 0.10 per cent C with about 1.5 per cent Cu and 0.25 per cent P had yield strengths in the range of 55,000 to 85,000 lbs. per sq. in. and elongation in the range 25 to 35 per cent in 2 in. In only a couple of cases did the Charpy impact values fall below 25 ft. lbs., most of the values ranging between 25 and 45 ft. lbs.

In low alloy structural steels of this class, without phosphorus as an alloying element, yield strengths of this order are accompanied by elongations below 25 per cent, unless considerable nickel is used, as is evidenced by Whetzel's[4] tabulation. It appears that phosphorus, judiciously used, has a specific action in elevation of the yield strength without as much loss of static ductility or formability as would be produced, were the higher yield obtained by raising the carbon.

Were it not for the impact limitation, very interesting static properties could be obtained in the high P, high Cu ranges, as Table 10 shows. This may be compared with Table 1 which deals with similar straight P steels. Such a comparison shows the beneficial effect of Cu or Ni, especially upon the repeated bend tests.

The low carbon sheets without Ni and with 0.50 per cent Ni and up to 0.30 per cent P were cold rolled in various steps with normal results as to increase of tensile and yield strengths and decrease of ductility.

At 10 per cent reduction in thickness by cold-rolling, the 0.50 per cent Ni steels were slightly stronger than in the absence of Ni, at all P contents used. This was true at 25 per cent reduction for a P content of 0.20 per cent or below, but the values for the 0.30 per cent P steel were not appreciably altered by Ni. At 50 per cent reduction there was little difference at any P content.

The 0.30 per cent P steel, at 50 per cent reduction gave a tensile strength of nearly 110,000 lbs. per sq. in. and a yield strength over 105,000 lbs. per sq. in., with an elongation in 2 in. of 2½ per cent. Yet, even in this hard condition the sheet could be doubled upon itself and hammered flat at the bend without signs of cracking, despite the impact brittleness of such a steel in the notched bar test.

Sheet of 22 gage was also made from some of the alloy combinations whose notched-bar impact properties were good. (See Table 5.) The static properties of these sheets are given in Table 11.

From the various tables in which static properties are presented it is seen that increase in yield strength is produced by phosphorus in company with quite a range of other elements usable in high yield strength steels.

(To be continued) P69-73

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